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Groundwater Modeling: Selection, Testing and Use. Volume 1

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Volume 1

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Task 20
September 1982
Water Management Division

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Groundwater models were applied to three field problems. The models were carefully selected and tested before use. Three different mass transport models were used at one site, and the results compared.

This study demonstrates a number of the strengths of groundwater modeling. A model can be used to test the reasonableness and consequences of working hypotheses developed through data interpretation. Modeling can be coordinated with data collection by helping to direct where new data should be collected. The model can then be updated and improved using the new data. Models can be used to simulate conditions under various management alternatives. The results help determine which management plan can best minimize the effects of contamination. Modeling can also be closely coordinated with the final design and implementation of a management plan, and can greatly extend the range of analysis possible in complex groundwater systems.

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GROUNDWATER MODELING:
SELECTION, TESTING & USE

by

David A. Hamilton

Task 20 of Groundwater Management Strategy for Michigan
Major Funding From Environmental Protection Agency Grant No. P00558801

September, 1982

Michigan Department of Natural Resources
Water Management Division

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D. Wiggert: Finite Element Modeling of Contaminant Transport

EXECUTIVE SUMMARY

The State of Michigan has developed the capability to use groundwater modeling through one task of an EPA 208 grant entitled "Groundwater Management Strategy for Michigan". The grant's overall goal is to develop a program to effectively prevent groundwater from becoming contaminated and to minimize the adverse impacts of known or suspected contamination cases through effective management. Complexities inherent in groundwater systems make traditional "hand calculation" techniques inadequate to provide the type of analysis necessary in modern resource management. Managers must be able to realistically evaluate the impacts of alternate management plans. Through effective analysis, managers are able to choose plans that are the most cost effective and adequately protect the resources. This study demonstrates that groundwater modeling is an effective analytical and management tool for complex hydrogeologic conditions typically found in Michigan.

A model is the simplification of reality into a useable form. It duplicates the response of the real system, and is used as a tool in studying the real system. There are many types of models. The first step in modeling is to understand the physical behavior of the system. Cause-effect relationships are determined and a "conceptual model" of how the system operates is formulated. The next step is to translate our physical understanding into mathematical terms, developing the governing equations with appropriate initial and boundary conditions. For simplified conditions these may be solved analytically; i.e. the simplified mathematical equations are solved exactly, typically with hand calculations, and the use of standardized tables and curves. Numerical solutions are needed for more general problems where there are irregular boundaries, heterogeneities or highly variable pumping or recharge rates. Computer techniques are required for the numerical solutions.

The data requirements for computer modeling are a frequently raised concern. Many seem to view a model as a very complicated thing that requires an unrealistic amount of data. It is more appropriate to view a model as a tool that is tailored to fit the scope and goals of a given project. The amount of data required is that which sufficiently defines the scope of a problem and provides enough information to meet the project goal. This is true regardless of the method of analysis. The model allows more effective use of the available data; more complexities can be accounted for; and the implications of assumptions used in the analysis and of management decisions can be evaluated.

It must be recognized that groundwater modeling is a very sophisticated tool. Groundwater modeling is a multi-disciplinary field incorporating elements of: hydrology (both surface and groundwater), geology, hydraulics, mathematics, and computer science. The interaction of these elements must be fully appreciated by those planning to apply groundwater models. Development of a program to utilize groundwater computer simulation requires expertise in these disciplines, and proper management and technical support.

The sophistication of groundwater modeling techniques leaves potential for misapplications and misunderstandings. Frequently the wrong model is chosen for a problem. This may be done because the limitations inherent in a given model are not understood and the model is misapplied. The other extreme of misapplication occurs when an overly sophisticated model is chosen for a problem. Sometimes the funding agency or client is disillusioned with the model results because unwarranted expectations are raised by modeler "oversell" during project planning. Often the solution technique is a mystery to all except the modeler. And finally, an obvious potential problem is model use by inadequately trained individuals.

When properly applied, groundwater models are very practical tools. The models can solve extremely complex groundwater flow problems and are now widely available. This study demonstrates a number of the strengths of groundwater modeling. A model can be used to test the reasonableness and consequences of working hypotheses developed through data interpretation. Modeling can be coordinated with data collection. The model can help direct where new data should be collected, and with new data the model can be improved. Models can be used to simulate conditions under various management alternatives. Results help determine which management plan can best minimize the effects of contamination. And although all these case studies have not yet reached design stage, modeling can be closely coordinated with the final design and implementation of a management plan. Groundwater models greatly extend the range of analysis possible in complex groundwater systems.

The use of groundwater models may generally be grouped into four categories. 1) Reconnaissance studies preceding field investigations. These utilize whatever minimal data may already exist describing site hydrogeology to try to determine what field conditions might be. 2) Interpretive studies during and following field data collection. The models help place varied and complex data into a comprehensive overall framework, and help demonstrate whether or not a given data interpretation is reasonable in the context of what is known about the entire groundwater system. 3) Predictive studies to estimate future flow patterns or contaminant plume movement under existing conditions or in response to various management options. 4) Studying various types of behavior by examining hypothetical or generic aquifer problems. The case studies demonstrate the value of models under various conditions.

The first case study was Southwest Ottawa County Landfill. Leachate contaminated the aquifer which supplies water to many area homes. The site hydrogeology and contamination plume outline were determined by installing monitoring wells and conducting a resistivity survey. The resistivity analysis was very helpful, it yielded detailed information on geometry and depths of low permeability lenses that were affecting the flow field and contaminant movement. The model was used to interpret all the field data and developed into a realistic simulation of the groundwater system. Low permeability lenses were incorporated into the model. Their complex effect on the flow field and contaminant movement could not be analyzed by any other means short of this type of modeling. The effects must be incorporated in order to properly evaluate the effectiveness of proposed purge well systems. *The groundwater system response was predicted for several possible purge well configurations. The model will be used to help design and implement an effective management plan.*

The second case study was in Comstock Township where contamination from an unknown source was found. Groundwater modeling was incorporated into the investigation to determine the source. A very simple flow model (for reconnaissance) was made using the almost negligible initial data. As the field work progressed, field data were incorporated into the model for interpretation. The model aided in understanding what might be happening in the aquifer system. The model can demonstrate the interrelationships between known data. It can test the reasonableness and consequences of hypotheses developed to explain aquifer behavior, and can help set criteria to be field checked. *This case study shows that it is possible to closely coordinate computer modeling with the field data collection. The model allows new interpretations to be rapidly incorporated to conform with new field data and an increasing complex data pool. Current theories and physical interpretations can be analyzed and a better understanding of the aquifer is developed.*

The final case study, Production Plated Plastics, was the focal point of the entire study. Several domestic wells near the plant were contaminated with chromium. A field investigation was started to define the extent of the contamination, but it was interrupted for two years. Models were made using existing information to predict where the plume may have gone. A flow model was developed to simulate the groundwater flow field and provided input to the mass transport models, which simulate the movement of the contamination plume. Physical complexities of the aquifer were successfully incorporated into the model. The model was coordinated with and helped direct the resumed field work. Projections based on the groundwater modeling analysis were different than those determined by hand calculations. Modifications to the field program based on the modeling turned out to be correct. The model was updated with new field data. A pump test was simulated before it was run, and the model was used to evaluate proposed purge well systems. *Groundwater models provide a means of simulating the dynamic response of a complex groundwater system. The impact of proposed activities, such as the location and pumping rates of purge wells, can be estimated before any money is invested in actually initiating the activity. This helps provide effective management.*

The models used were selected after a careful review of available models. Each model was tested to gain familiarity with, and confidence in the model. An individual model is not applicable to all situations. Each model has its unique set of assumptions, strengths and weaknesses. Each project must be carefully evaluated, project goals set, and the analytical needs determined. This was done for each case study.

SECTION I

BACKGROUND

CHAPTER 1

INTRODUCTION

A groundwater modeling program has been initiated as one task of an EPA 208 grant entitled "Groundwater Management Strategy for Michigan". The grant's overall goal is to develop a program to effectively prevent groundwater from becoming contaminated and to minimize the adverse impacts of known or suspected contamination cases through effective management. Groundwater modeling is an analytical tool, and ultimately a management tool that is being developed to help meet this goal.

The groundwater modeling task is to develop and test a basic modeling capability and use it to assist in evaluating the groundwater impacts at three of the pollution incidents being evaluated in detail as part of this grant. The three sites are Southwest Ottawa County Landfill, Comstock Township, and Production Plated Plastics; their locations are shown in Figure 1-1.

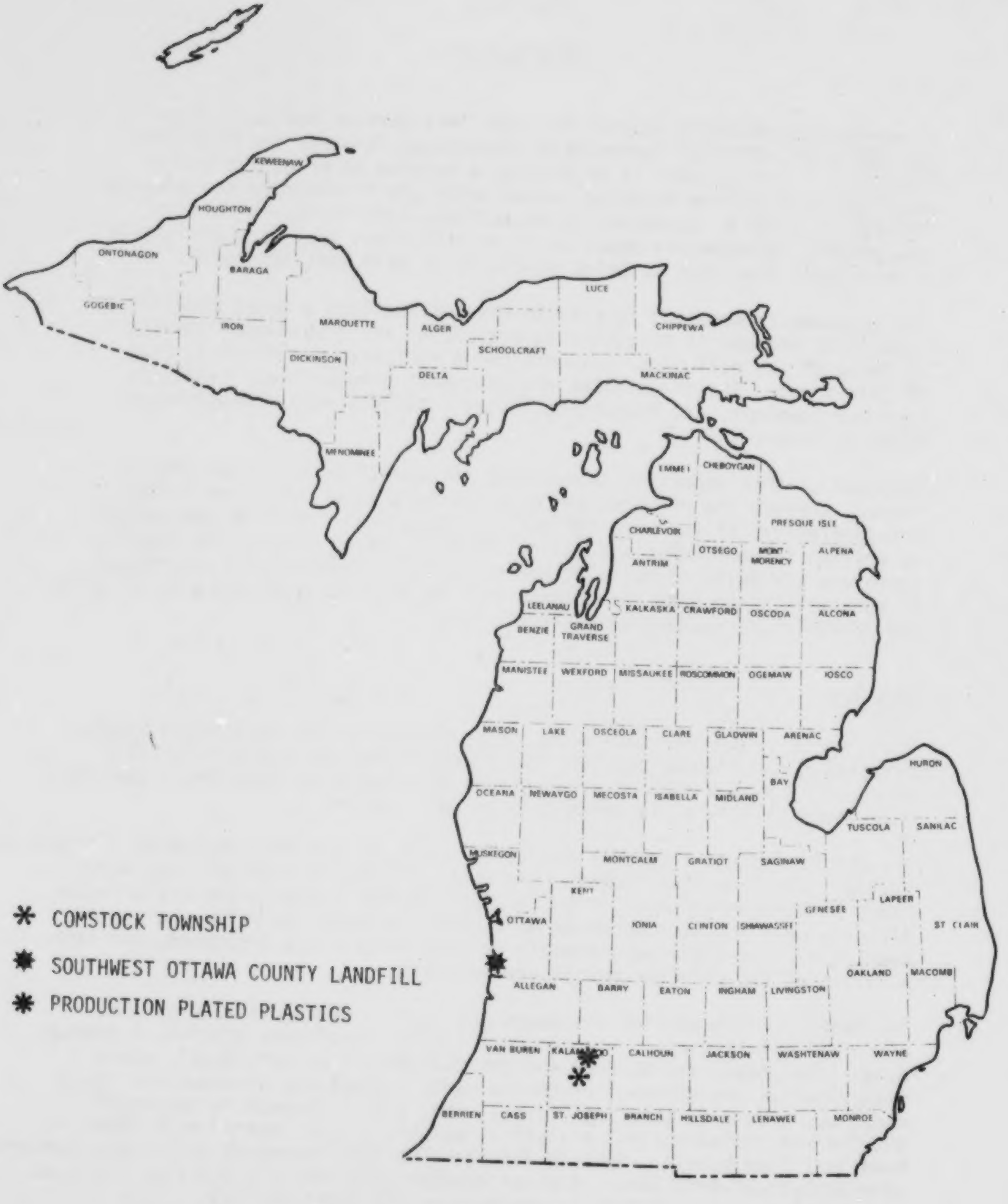
The goal of this report is to describe in detail the work that was performed, present the results, and make specific as well as generalized interpretations of the work and methodologies used. Much of the report is written in considerable technical detail. It is intended to benefit those who are going to actually use groundwater models. The experience is conveyed in the hope that others will be able to avoid the same problems and directly use successful methodologies.

Overview

This report is divided into seven major sections. The Background Section contains a brief description of groundwater modeling. This is written to provide someone without a background in groundwater modeling a conceptual understanding of what is being done in this report.

The second section discusses the model selection process, including a literature review. The literature review references a range of material from very basic background information to the most current state-of-the-art articles. Although many computer programs have been developed, very few are readily available. The model requirements for the project are discussed, and capabilities of the selected models are outlined.

The Model Testing Section discusses the testing done with each of the numerical models used. The principal models tested were AQUIFEM, a groundwater flow model, and GEOFLOW and the USGS Mass Transport Model, where both simulate the movement of contaminants through the groundwater. Each model was tested to gain familiarity with, and confidence in the model. AQUIFEM was tested against analytical solutions and compared with other numerical flow models. GEOFLOW and the USGS Mass Transport Model were compared with analytical solutions. A mass transport problem in a 2-D flow field was also simulated with GEOFLOW to demonstrate its applicability.


KEWEENAW
HOUGHTON
ONTONAGON
BARAGA
GOGEBIC
IRON
MARQUETTE
ALGER
LUCE
CHIPPEWA
SCHOOLCRAFT
DICKINSON
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ST. JOSEPH
BRANCH
HILLSDALE
LENAWEE
MONROE
* COMSTOCK TOWNSHIP
✸ SOUTHWEST OTTAWA COUNTY LANDFILL
✸ PRODUCTION PLATED PLASTICS

FIGURE 1-1 Location of Case Studies

The Case Studies Section is the heart of the report. In the first case study, leachate from Southwest Ottawa County Landfill has contaminated nearby domestic wells. The site hydrogeology and contamination plume outline were determined by installing monitoring wells and conducting a resistivity survey. The resistivity analysis was very helpful, it yielded detailed information on geometry and depths of low permeability lenses that were affecting the flow field and contaminant movement. The model was used to interpret all the field data and developed into a realistic simulation of the groundwater system. Low permeability lenses were incorporated into the model. Their complex effect on the flow field and contaminant movement could not be analyzed by any other means short of this type of modeling. The effects must be incorporated in order to properly evaluate the effectiveness of proposed purge well systems. The groundwater system response was predicted for several possible purge well configurations. The model will be used to help design and implement an effective management plan.

The second case study was in Comstock Township where residential wells were contaminated with chlorinated hydrocarbons from an unknown source. Groundwater modeling was incorporated into the investigation to determine the source. A very simple flow model was made using the almost negligible initial data. As the field work progressed, field data were incorporated into the model for interpretation. The model aided in understanding what might be happening in the aquifer system. The model can demonstrate the interrelationships between known data. It can test the reasonableness and consequences of hypotheses developed to explain aquifer behavior, and can help set criteria to be field checked. This case study shows that it is possible to closely coordinate computer modeling with the field data collection. The model allows new interpretations to be rapidly incorporated to conform with new field data and an increasing complex data pool. Current theories and physical interpretations can be analyzed and a better understanding of the aquifer is developed.

The final case study, Production Plated Plastics, was the focal point of the entire study. Several domestic wells near the plant were contaminated with chromium. A field investigation was started to define the extent of the contamination, but it was interrupted for two years. Models were made using existing information to predict where the plume may have gone. A flow model was developed to simulate the groundwater flow field and provided input to the mass transport models, which simulate the movement of the contamination plume. This case study was used for an in-depth comparison of mass transport methodologies. This provided an important opportunity to critique and evaluate the models.

Physical complexities of the aquifer were successfully incorporated into the model. The model was coordinated with and helped direct the resumed field work. Projections based on the groundwater modeling analysis were different than those determined by hand calculations. Modifications to the field program based on the modeling turned out to be correct. The model was updated with new field data. A pump test was simulated before it was run, and the model was used to evaluate proposed purge well systems. Groundwater models provide a means of simulating the dynamic response of a complex groundwater system. The impact of proposed activities, such as the location and pumping rates of purge wells, can be estimated before any money is invested in actually initiating the activity. This helps provide effective management.

The Evaluation and Conclusions Section contains a general discussion and evaluation of the modeling approach and its applicability; and a summary and conclusions chapter. The bibliography contains selected references used in the study. And the appendices contain reports submitted by Dr. David Wiggert, Michigan State University, and Dr. Steven Wright, University of Michigan. They assisted in the mass transport modeling. Appendix A is a very brief assessment of using a two-dimensional flow model at Southwest Ottawa County Landfill as opposed to using a three-dimensional model. Wiggert supported the methodology used in this study at Southwest Ottawa County Landfill. Appendices B and C are Wright's reports on estimating contaminant transport parameters and applying the USGS Mass Transport Model at Production Plated Plastics. Appendix D is Wiggert's report on testing GEOFLOW and applying it at Production Plated Plastics.

CHAPTER 2

GROUNDWATER MODELING

A model is the simplification of reality into a useable form. It duplicates the response of the real system, and is used as an analytical tool in studying the real system. The first step in modeling is to understand the physical behavior of the system. Cause-effect relationships are determined and a "conceptual model" of how the system operates is formulated. This type of model is very powerful, and is fundamental to an understanding of any process or system. However, quantitative analyses cannot be based on a conceptual model. For example, we cannot estimate what effect a major new well field would have on the flow system, or what the concentration of a contaminant plume might be in a year.

The next step in making a more useful model is to translate the physical understanding into mathematical terms, developing the governing equations with appropriate initial and boundary conditions. For simplified conditions these may be solved analytically. An analytical solution is the exact mathematical solution of the governing equation. This can only be accomplished under very idealized and simplified boundary and initial conditions. A classic and widely used analytical solution is the Theis equation. It is used to calculate the effect of unsteady flow to a well in a confined aquifer. Some of the simplifying assumptions are: a fully penetrating well with a constant pumping rate; a homogeneous, isotropic, infinitely extensive aquifer with constant thickness; the aquifer storativity is constant; and water is immediately released from storage upon decline of the head. Many techniques and adjustments have been developed which attempt to relax some of the stringent assumptions. These, however, are usually quite limited themselves and often become cumbersome.

Numerical solutions are needed for more general problems where there are irregular boundaries, heterogeneities or highly variable pumping or recharge rates. Numerical models replace continuous variables (as used in analytical models) with discrete variables. Computer techniques are used for the numerical solutions. Computer simulation, or modeling, allows more realistic representation of the physical complexities found in aquifer systems than can normally be accounted for with traditional analytical calculations. Computers solve the partial differential equations which govern groundwater flow and pollutant transport. The equations can be formulated in many different ways, as can the initial and boundary conditions, and solution techniques. Therefore, many different computer programs are possible, and a very large array has been developed. Each one is based upon a certain set of assumptions and has inherent limitations. No one program will be appropriate for every circumstance, and many programs are developed for very specific applications.

Study objectives and available data must be carefully evaluated to determine what the modeling needs are at each site. An appropriate computer program can then be selected to meet that need.

The data requirements for computer modeling are a frequently raised concern. Many seem to view a model as a very complicated thing that requires an unrealistic amount of data. It is more appropriate to view a model as a tool that is tailored to fit the scope and goals of a given project. The amount of data required is that which sufficiently defines the scope of a problem and provides enough information to meet the project goal. This is true regardless of the method of analysis. The model allows more effective use of the available data; more complexities can be accounted for; and the implications of assumptions used in the analysis and of management decisions can be evaluated.

The use of groundwater models may generally be grouped into four categories. 1) Reconnaissance studies preceding field investigations. These utilize whatever minimal data may already exist describing site hydrogeology to try to determine what field conditions might be. 2) Interpretive studies during and following field data collection. The models help place varied and complex data into a comprehensive overall framework, and help demonstrate whether or not a given data interpretation is reasonable in the context of what is known about the entire groundwater system. 3) Predictive studies to estimate future flow patterns or contaminant plume movement under existing conditions or in response to various management options. 4) Studying various types of behavior by examining hypothetical or generic aquifer problems.

The basic steps in modeling are always the same. First the problem must be clearly stated, and it must be decided what is to be solved for in the model. All the available data must be gathered, evaluated, and missing data obtained or estimated. An assessment must be made to determine what the best modeling approach is for that case. The data must be schematized - the aquifer geometry "idealized", and initial and boundary conditions determined. Aquifer geometry includes aquifer bottom elevations, confining layer elevations, as well as other physical considerations such as where an aquifer pinches out. Initial and boundary conditions have both physical and mathematical significance. A differential equation cannot be solved without some known conditions. Initial conditions are those that exist at the beginning of the simulation period. The two most common boundary conditions are "no flow" and "specified head". No groundwater flows across a no flow boundary. Such a boundary occurs along a groundwater divide, along a streamline, and where an aquifer pinches out. Specified head boundaries occur where the piezometric elevation is known; this is frequently used along lakes and major rivers. Other boundary conditions that must be estimated include areal recharge and leakage (if significant) from adjacent aquifers.

The appropriate governing differential equation must be determined along with an appropriate solution technique or computer program. The assumptions made in an equation's formulation determine what its appropriate applications are. Model parameters must be determined, such as: hydraulic conductivity, storage coefficient, porosity, dispersion coefficients and retardation factors.

The model must be calibrated against some known standard. This is usually a trial and error process to refine initial estimates of parameters and boundary conditions, in order to reproduce some known aquifer behavior. A typical situation is where the piezometric head is known at several points. The model is run using initial parameter and boundary condition estimates. The input is varied until the model reasonably reproduces the known heads. Other factors such as seepage velocities and discharge volumes must also be taken into consideration.

An important part of groundwater modeling is sensitivity analysis. This is where potentially significant input values are systematically varied over their range of uncertainty. This helps determine the impacts of estimated parameters.

Once a satisfactory model is obtained, the computed results must be interpreted and management alternatives can be examined.

SECTION II

MODEL SELECTION

CHAPTER 3

LITERATURE REVIEW

There is a wealth of literature available on groundwater modeling. Several articles provide excellent summaries of what groundwater modeling is, and what the state-of-the-art is. A series of articles published in GROUNDWATER (Mercer and Faust, 1980) give a good overview of groundwater modeling, and discuss mathematical and numerical models, model applications, and recent developments. They are written to give someone with no background in the field a basic understanding of groundwater modeling. Two good basic groundwater texts for additional background are Groundwater by Freeze and Cherry (1979) and Hydraulics of Groundwater by Bear (1979).

Prickett (1979) presented a brief discussion of the state-of-the-art. Prickett has had many years of modeling experience and co-authored a groundwater flow model that is probably the most widely used. He raised a number of issues about how models are abused, and conversely how they are very practical tools when properly used. He cautioned that there are three main factors in the use of groundwater models that can make them little more than intellectual toys. First, the wrong model is frequently chosen for a problem. Sometimes this is done by overkill, where an overly sophisticated model is used. Second, the paying agency or client is often disillusioned with the model results because of unrealistic expectations in the early stages of project planning. And finally the solution technique is often a mystery to all except the modeler himself.

According to Prickett there are three main factors that make groundwater models very practical tools. The models can solve extremely complex groundwater flow problems. The models are widely available. And the computer code and input data provide a perfect means of transferring to another person the exact solution technique and input parameters used.

Anderson (1979) presented an excellent and quite detailed review of mass transport modeling. She explained some of the basic theory, summarized theoretical development work, and went into some detail in reviewing published modeling techniques and results. Mass transport modeling is a very complex area where a lot of basic research is still ongoing. It is not yet possible to put a great deal of confidence in the results of mass transport models. There are uncertainties in determining the input data, especially velocity distributions and dispersivities; and there are inherent numerical difficulties involved in the solution techniques. In spite of the uncertainties, a mass transport model can be a useful tool to aid in the planning process. Incorrect predictions by models have generally been a result of incorrect definition of the medium properties and poor choice of boundary conditions rather than problems with the mathematical modeling scheme. The acquisition of reliable data is the "critical limiting factor" in the application of any model to field situations.

There are many published modeling case studies, both actual field situations and hypothetical studies. Some of the ones reviewed in preparation for this study may be found in the selected reference section. Several literature reviews have been made. In addition to a review by Anderson (1979), which was directed specifically toward mass transport modeling, there is a more general review by Knox and Canter (1980). They categorize the types of models used and their applications, and provide an annotated bibliography of 250 references.

Bachmat, et al (1980) made a detailed review of 250 groundwater models that have been developed. They categorize models by capabilities and uses. Information about each model is tabulated by: general identification characteristics, the model's conceptual and mathematical framework, the computer program, documentation, availability of the program, and existing model applications.

Only 30 of the 250 surveyed models can be classified as "useable". These have been completely documented, are available, and have been applied to at least one field problem. This situation seems to result from restrictions on availability of codes developed by private and semi-public agencies; poor documentation of programs, particularly those developed at universities; and difficulties in applying existing programs to field problems.

The detailed information gathered by Bachmat, et al (1980) is available on computer files at the International Groundwater Modeling Center.* They will provide a summary listing of all the models in their files; a more detailed annotation of requested models; and they will conduct a search of their files for a model that will meet specified requirements. These services are provided at a relatively nominal charge. They do not directly provide documentation or assistance in model useage. It is up to the individual to contact the model developer.

The literature review indicated that groundwater modeling has been used for several years, and is a powerful analytical and management tool. Flow models are highly developed, the modeling techniques are very reliable, and the limiting factor in an applied model's reliability is the availability and accuracy of field data. The models are capable of simulating very complex situations, including: irregular boundaries, unsteady state, heterogeneous and anisotropic medium, time varying boundary conditions, three-dimensional analysis (data requirements greatly limit the practicality of 3-D analysis), and varying pumpage and recharge. Mass transport models are not as well developed, but are still useful tools. Mathematically it is possible to incorporate very complex physical and chemical mechanisms that affect contaminant concentrations. However, most of the mechanisms

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are poorly understood. There is still controversy about the nature of dispersivity. Dispersivity is the parameter used in modeling to account for the dispersion/diffusion process. Current research is directed toward investigating scale-dependent dispersion (Pickens and Grisak, 1981). There are indications that near a source (apparently within the first few meters) the dispersivity increases with distance traveled, but it asymptotically approaches a maximum value. For regional scale problems it is usually considered a constant parameter. The current general practice is to determine the dispersivity through calibration of the model; there are no efficient or generally accepted field tests. Interaction between contaminants and soil particles is generally represented by a linear adsorption isotherm. In the model this can be accounted for by a retardation factor, which adjusts the mean contaminant velocity to some proportion of the mean seepage velocity.

There are several numerical techniques available: finite difference, finite element, method of characteristics, and boundary integral equation method. Advantages and disadvantages abound for each technique; the individual application determines which is most appropriate.

For example, it is known that the finite-element method will provide an accurate numerical solution of the flow problems. And finite elements are very versatile and easily applied to irregular boundaries. However, applying the method to mass transport is numerically more difficult and produces less accurate results because the mass transport equation contains a convective as well as a dispersive term (Pinder and Grey, 1977). The finite element method of numerically subdividing the study area, coupled with the methods used in incorporating a time step, produces an oscillation along the solute propagation front (termed undershoot/overshoot), as well as numerical dispersion, which tends to smear the front. This is especially a problem when convective transport dominates over diffusive transport. Pinder and Grey (1977) discuss procedures that partially minimize these effects. O'Neill (1981) reports improved solutions for one-dimensional mass transport by employing time-variable grid sizing. However, for two-dimensional problems such techniques apparently remain in developmental stages.

In Appendix D Wiggert discussed two criteria that can be utilized to assess the accuracy of a numerical model to simulate mass transport. One can define a numerical Peclet number

$$Pe = \frac{v\Delta\ell}{D_\ell} = \frac{\Delta\ell}{\alpha_\ell}$$

in which v is the fluid velocity, $\Delta\ell$ a representative grid length, D_ℓ is the dispersion coefficient in the ℓ-direction, and α_ℓ is the dispersivity in the ℓ-direction. The Peclet number can be interpreted to indicate the prominence of convection relative to dispersion in the mass transport phenomenon. The second term is the numerical Courant number

$$Co = \frac{v\Delta t}{\Delta \ell}$$

in which Δt is the time step. This parameter is indicative of the distance a trace element has traveled relative to the grid size.

In a strict sense these numbers are applicable only to one-dimensional flows and mass transport, but they can provide an approximate guideline for simulation of two-dimensional flows or mass transport. *A frequently adopted procedure is to maintain Pe not much greater than unity, and to treat unity as an upper bound on Co (O'Neill, 1981). In regional aquifer situation, the Courant condition usually can be satisfied with no difficulty; however, it may be difficult to maintain low Pe numbers. Associated with high Pe is the undesirable aspect of numerical oscillation of concentration fronts.*

CHAPTER 4

MODEL SELECTION

The groundwater modeling effort has two major components: flow modeling which simulates the groundwater hydraulics; and mass transport modeling which simulates the pollutant movement. Separate programs are used for each component.

Flow Models

Study objectives and available data were carefully evaluated to determine the modeling needs at each site. These are discussed in detail in each case study. Rather than obtain a separate program for each case study that would meet its specific requirements, it is more advantageous to obtain one flow model with a fairly general formulation that would be applicable to our varied sites and most of the general problems we are likely to have. A two-dimensional model would be adequate, and it would have to handle the following conditions: heterogeneous, anisotropic aquifer; steady and non-steady state solutions; phreatic or confined or changing status aquifer; spatial variation of aquifer characteristics; varied boundary conditions, possibly including interrelationships with surface waters; temporal variation of boundary conditions; recharge; and possibly leakage.

Many programs have been developed which meet most or all of these requirements. The major problems are: most of the programs are not readily available; some of these programs were developed for very specific applications and were not tested for general application; others are proprietary; and very few have adequate documentation.

There are principally three programs that meet most of our requirements: 1) the Prickett-Lonnquist model (1971) from the Illinois State Water Survey; 2) the U.S. Geological Survey model, written by Trescott, Pinder and Larson (1976), and 3) AQUIFEM-1, AQUIfer Finite Element Model, developed at MIT by Townley and Wilson (1980). Of these, only AQUIFEM-1 can directly provide the steady state solution. AQUIFEM is a versatile program that meets all our requirements. It can more easily handle complex boundary conditions and it has by far the best documentation. There are a couple of other programs that have recently been released, but AQUIFEM provides more flexibility and better documentation. The author also had previous experience with an earlier version of AQUIFEM.

Following is a list of some of the characteristics and capabilities of AQUIFEM:

- Finite element formulation, linear triangular elements
- 2-D horizontal
- 2-D vertical (for some conditions)
- Transient or steady state
- Heterogeneous
- Anisotropic
- Phreatic or confined aquifer
- Change in aquifer status between confined and phreatic
- Leaky or non-leaky
- Time varying boundary conditions
- Natural or artificial recharge
- Relations of water exchange between the aquifer and fully or partially penetrating surface water bodies
- Evapotranspiration
- Pumping or recharge wells
- Springs, drains
- Discharge to surface depressions
- Effects of geologic faults

Minor program changes were made to make the program compatible with the state's Burroughs 7700 computer. The Burroughs could not pass all the components of a major matrix ("A") through the "CALL" statement. The matrix had to be broken into its components and passed through "COMMON". As a result, much of the dynamic dimensioning advantage that was written into AQUIFEM was lost, requiring greater computer core memory. Other minor changes in input and output were made. The input was changed so the first five columns contained a card ID for easy identification when changing the data file. A calculation of seepage velocity was added; and so was the capability of writing piezometric heads and coordinates to a disk file for later use in a contouring program.

Mass Transport Models

Mass transport modeling is a much more complex and less well defined process. A two-dimensional mass transport model that is capable of handling the velocity fields produced by the flow model is needed. It should include dispersion, preferably with a means of adjusting the dispersion coefficient if the velocity changes; and it may be necessary to incorporate adsorption (probably through a retardation coefficient). Again the major problems in model acquisition are availability, documentation and testing for general applications.

Contracts were made with Dr. David Wiggert from Michigan State University and Dr. Steven Wright from University of Michigan to assist in the transport modeling phase. Wiggert worked on testing GEOFLOW and applying it at the

Production Plated Plastics site. Wiggert was involved in the initial development of GEOFLOW. Additional work on it has been done at D'Appolonia (1980), where they are developing GEOFLOW as part of a package to assess the hydrologic impacts of strip mines in Kentucky. Following is a list of some of the characteristics and capabilities of GEOFLOW:

- Finite element formulation, linear quadrilateral elements
- 2-D horizontal
- Flow model
- Mass transport model
- Transient or steady state
- Time variable adsorption coefficient
- Time variable dispersion coefficients
- Acid front migration
- Spatial variation of adsorption coefficient
- Radionuclide decay constant
- Time variable pumping rates
- Heterogeneous
- Anisotropic
- Phreatic or confined
- Recharge

The majority of Dr. Wright's work dealt with determining appropriate dispersion and adsorption coefficients for use in this study. He also spent some time applying the USGS Mass Transport Model (Konikow and Bredehoeft, 1978) to Production Plated Plastics. Because of the uncertainty present in mass transport modeling, it was decided that the use of two different numerical formulations would provide useful comparisons and checks for the purposes of this study. Following is a list of some of the characteristics and capabilities of the USGS Mass Transport Model:

- Method of characteristics formulation for mass transport, finite difference for flow, rectangular elements
- 2-D horizontal
- Flow model
- Mass transport model
- Transient or steady state
- Non-reactive solute
- Constant dispersion coefficient
- Heterogeneous
- Anisotropic
- Pumping and recharge

There are two other mass transport programs that became available after the selection process that merit further consideration. Segol (1976) developed a three-dimensional finite element mass transport model while she was at the University of Waterloo. The 2-D flow part of this model has been applied in a field situation. The User's Manual has been updated and should now be available from the University of Waterloo. Prickett, et al (1981) have developed a "Random Walk" Solute Transport Model. Flow is calculated by a finite difference technique based on Prickett and Lonnquist (1971). The solute transport portion is based on method of characteristics (or particle-in-a-cell method) for the convective mechanisms, and a "random walk" technique (a statistical approach) for the dispersion effects. This shows some interesting potential, particularly to avoid numerical dispersion problems common in other techniques, and possibly improved efficiency over the USGS mass transport model.

Cleary and Ungs, from Princeton University, developed a set of analytical solutions to several mass transport problems. The analytical solutions are very complex, so computer programs were written to evaluate the integrals. These solutions are valid for very idealized situations. However, the programs are very easy to use, and for many problems they can give at least good first order approximations. They also provide a means of checking numerical mass transport models. For the assumed conditions, the analytical solutions are exact.

The analytical solutions were developed for constant sources. They were modified by the author of this report to also represent a slug source. This was done using the principles of linear superposition. The modification extends the applicability of the models to many more situations.

Computer Graphics

An important factor in any analysis is the presentation of the results. In computer simulation, a certain amount of computer graphics is helpful for analysis during the modeling process, and very useful in presenting the final model results to others.

MIT supplied a simple Calcomp plotting routine to plot the finite element grid. It is essential to plot a grid to make sure there are no errors in it. AQUIFEM includes a page plot of piezometric heads at nodes, which can easily be contoured by hand. This is an adequate aid in most cases for analyzing model output. For presentation of final model results, it is usually faster and more accurate to generate the contour map by computer than by hand. Many sophisticated techniques in computer contouring have been developed. The general principle is to take "random" data, "post" them to a uniform grid, and then using an interpolation routine, generate the contours from the "posted" grid. The "random" data are the nodal piezometric heads. Because of the finite element grid design, they are usually scattered in a variable density network, with an irregular overall boundary.

These factors caused problems with the sophisticated programs when "posting" the data. "Posting" is developing a uniform grid and assigning head values to the grid based on the nonuniform finite element nodes. Various weighting procedures and search radiuses can be used. Two programs were tried, an in-house one developed in the Michigan Department of Transportation and SURFACE II from Kansas State. They were both quite expensive to run and the results were not satisfactory. The variable density grid and irregular boundaries caused oscillations in the "posted" or interpolated values. There are some very expensive and very sophisticated computer graphics packages which are supposed to be able to handle these problems satisfactorily. This would have to be demonstrated, but in any case, they are cost prohibitive. A very simple linear interpolation routine was used to meet the need for a contouring program. This routine linearly interpolates along the sides of the linear triangular elements, and connects the points of equal value across the element. The technique is very simple, inexpensive to run, and gives quite satisfactory results. SURFACE II was used for some of the GEOFLOW results, where the grid became so dense that acceptable contours were generated.

SECTION III

MODEL TESTING

CHAPTER 5

MODEL TESTING

AQUIFEM

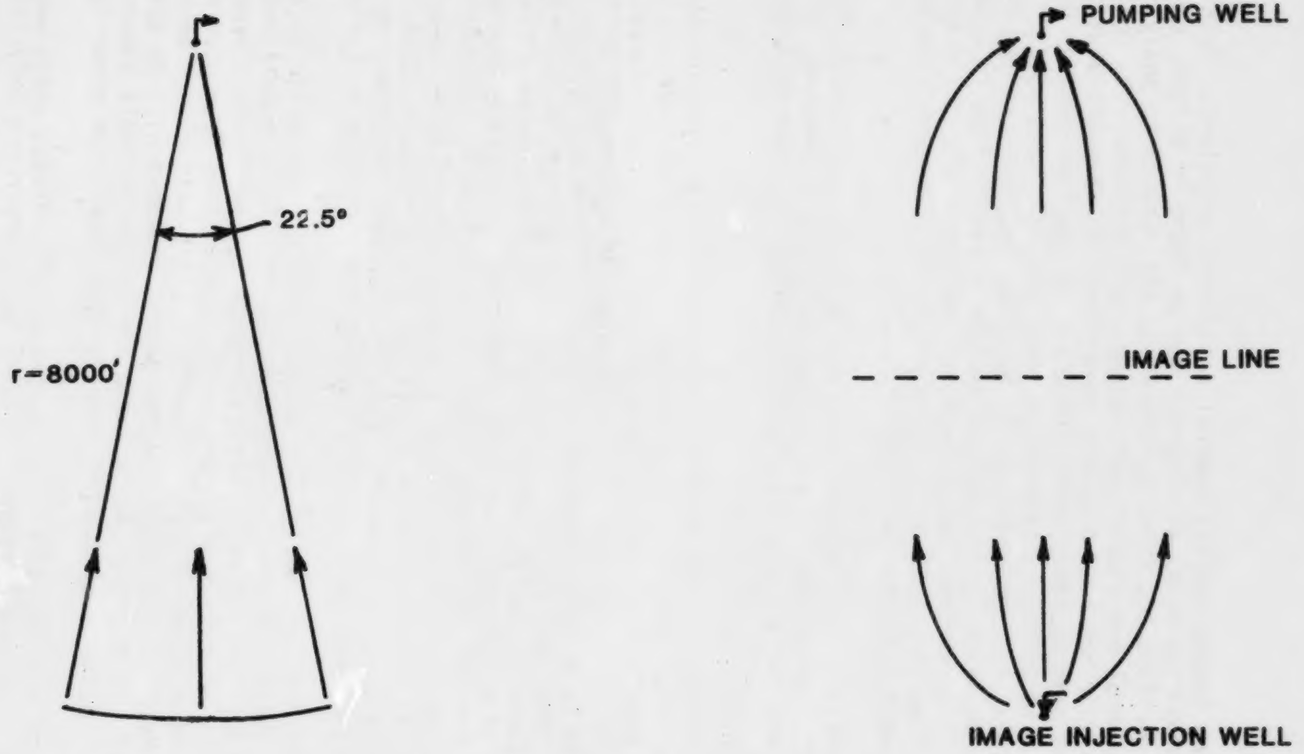
AQUIFEM has been tested against several analytical solutions. Details of testing done during model development may be found in Wilson, et al (1979). They verified the model by comparing its results to analytical solutions of several one-dimensional steady state problems: 1) Confined aquifer with prescribed head boundary conditions; 2) Phreatic aquifer with prescribed head boundary conditions; and 3) Confined aquifer with leaky inflows. In addition, several unsteady problems were used: 4) One-dimensional confined aquifer; 5) Confined aquifer - radial flow to a well with no leakage; 6) Confined aquifer - radial flow to a well with leakage; 7) Unconfined one-dimensional aquifer - similarity solution; and 8) Radial flow to a well with change of status. Results from AQUIFEM compared very well with the analytical solutions.

Two example problems were included with the magnetic tape and documentation supplied by MIT. After AQUIFEM was put on the state's computer, the example input was run and the results were exactly the same as those supplied by MIT.

The model was further tested against analytical solutions to increase confidence in the model and start becoming familiar with it. The analytical solutions are widely used and available from many published sources, for example Bear (1979). The first test simulated the piezometric surface drawdown caused by a fully penetrating pumping well in a confined, leaky aquifer. The test used the same radial grid that Wilson, et al (1979) used. Since there is radial symmetry, only a 22.5^{o} sector of a circle with a radius of 8,000 feet, was used. The other parameters used were: pumping rate, $Q = 160{,}000\ ft^3/day$; storativity, $S = 10^{-3}$; transmissivity, $T = 10^5$; ratio of leaky layer hydraulic conductivity to leaky layer thickness, $K'/b' = .1$; $\beta = (T/(K'/b')) = 10^3$; and the drawdown $= (Q/(4\pi T)) \times W(u, r/\beta)$ where $W(u, r/\beta)$ is the leaky aquifer well function. A transient analysis was made, and the results are presented in Table 5-1.

The results compare very well. The only significant deviation is at the well ($r = 1$), where the drawdown predicted by AQUIFEM is consistently less than the analytical solution. This is because in the finite element formulation the node value represents an average piezometric head over one third of the surrounding element area. Therefore, there will always be an error in predicted heads at the pumping node, actual drawdown will be greater than predicted. This error can be minimized by having small elements around a pumping node. Beyond the pumping node itself the error is negligible.

The second test used the same grid and parameters, except there was no leakage ($K'/b' = 0$) and drawdown $= Q/(4\pi T)\ W(u)$, where $u = Sr^2/(4Tt)$ and t is time. Results compare very well (see Table 5-2) for small times,


22.5°
r=8000'
PUMPING WELL
IMAGE LINE
IMAGE INJECTION WELL

a) AQUIFEM simulation

b) Method of images simulation

FIGURE 5-1 Comparison of flow patterns.

TABLE 5-1

LEAKY CONFINED AQUIFER
COMPARISON BETWEEN AQUIFEM AND ANALYTICAL SOLUTION

Radial Distance (feet)	DRAWDOWN $t = .0033$ day Analytical	 $t = .0033$ day AQUIFEM	 $t = .0103$ day Analytical	 $t = .0103$ day AQUIFEM	 $t = \infty$ Analytical	 $t = \infty$ AQUIFEM
1	1.78	.94	1.78	1.02	1.79	1.05
125	.47	.44	.52	.52	.57	.55
250	.28	.28	.36	.36	.39	.38
500	.14	.13	.21	.20	.235	.24
1000	.03	.03	.09	.08	.107	.10
2000			.015	.013	.029	.027
8000					.000038	0 (boundary)

TABLE 5-2

CONFINED AQUIFER, NO LEAKAGE
COMPARISON BETWEEN AQUIFEM AND ANALYTICAL SOLUTION

Radial Distance (feet)	DRAWDOWN $t = .01$ day Analytical	 $t = .01$ day AQUIFEM	 $t = .03$ day Analytical	 $t = .03$ day AQUIFEM	 $t = 10^6$ days Analytical*	 $t = 10^6$ days AQUIFEM
1	1.86	1.13	2.0	1.26		
125	.63	.62	.77	.76	1.26	1.05
250	.46	.45	.60	.58	1.02	.87
500	.29	.28	.42	.41	.87	.70
1000	.13	.13	.25	.24	.69	.52
2000	.028	.026	.106	.099	.49	.35
4000	.0005	.001	.0166	.015	.28	.17
8000			.0001	0 (B.C.)	0 (B.C.)	0 (B.C.)

*Incorporating method of images

until the drawdown intersects the boundary condition at $r = 8,000$ feet. After this point AQUIFEM maintains zero drawdown while the analytical solution continues to draw down. This points out the importance of boundary conditions. They must be carefully considered in an analysis, as they can greatly affect the solution. An attempt was made to reproduce the boundary conditions used in AQUIFEM analytically through the method of images. This involves placing an injection well 16,000 feet from the pumping well. The withdrawal and injection rates are equal, and the analytical solutions are linearly superimposed. This analytical solution at $t = 10^6$ days is compared with the steady state solution from AQUIFEM. The results are not identical because the boundary conditions are not identical. In the AQUIFEM run a circular recharge boundary encircling the well is assumed, with perfectly radial flow; whereas the method of images analysis used a recharge "wall". The flow patterns are shown in Figure 5-1. Head losses would be expected to be less for the AQUIFEM boundary conditions, and this is evident in the results. To more accurately reproduce the AQUIFEM results would require many image recharge wells surrounding the pumping well. Results are very close in early times because the boundary conditions are the same. At these times both analyses are using essentially radial flow, with the water withdrawn from storage.

These additional tests further demonstrate the accuracy of AQUIFEM and the importance of boundary conditions on the solution. Other minor testing was done to make sure the program options worked and to gain familiarity with the program.

AQUIFEM - USGS Flow Model - FICA

Flow model testing was completed by running a common problem and comparing the solution from AQUIFEM with those from the USGS flow model and FICA (the predecessor of GEOFLOW, developed at Michigan State University). The test problem is from the USGS flow model documentation (Trescott, et al, 1976). A sketch of the boundary conditions is in Figure 5-2. The aquifer is confined and homogeneous, with two pumping wells and one recharge well, surrounded by a no flow boundary, except for one reach with a specified head. (Norm Granneman of the USGS Lansing District Office ran the USGS flow model, and Steve Miller of the Water Management Division ran FICA).

Each model used a 30 day time step. The withdrawal rate was doubled after 600 days to complicate the problem. USGS used the densest overall grid, with uniform 5000' x 5000' elements, a total of about 400 nodes and 324 elements, not including those describing boundary conditions. For FICA, 10,000' x 10,000' elements were used for most of the grid, with smaller triangular elements used near the wells. This resulted in 107 nodes and 96 elements. The AQUIFEM model had the fewest nodes, using triangular elements with a base of 20,000' and height of 10,000' for most of the grid, and smaller elements near the wells (very similar to those used in FICA). A total of 67 nodes and 107 elements were used. Results are compared in Tables 5-3 and 5-4. *In general, the results are reasonably close. The greatest differences tend to occur at early times and at the recharge well.*

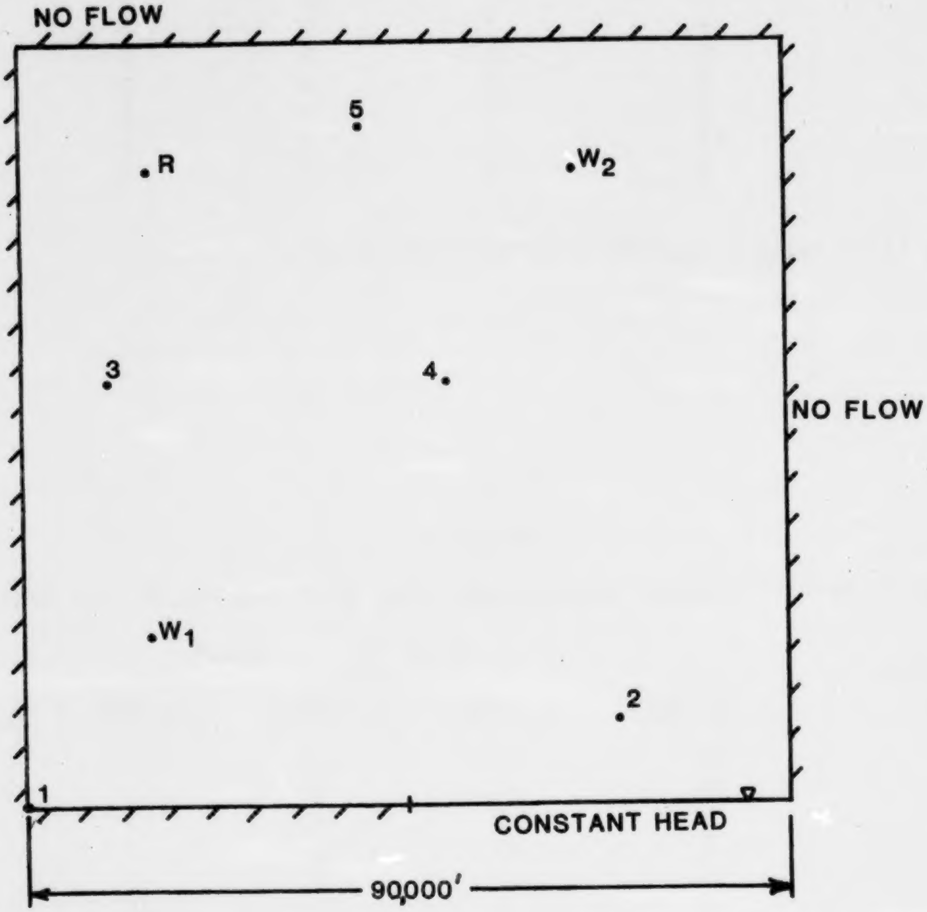

NO FLOW
5
R
W2
3
4
NO FLOW
W1
2
1
CONSTANT HEAD
90,000′

FIGURE 5 2 Problem characteristics used to compare GEOFLOW, FICA and the USGS flow model. Numbered points are where model results are compared.
Pumping wells: $W_1 = W_2 = 2$ ft^3/sec (doubled after 600 days)
Recharge well: $R = 2$ ft^3/sec
Transmissivity: $T_X = T_Y = 0.1$ ft^2/sec

TABLE 5-3

Variation of resulting heads, between FICA and AQUIFEM for test problem

Observation Point	% Difference in Heads*				
	t = 300 days	t = 600	t = 1200	t = 1800	t = 3000
1	8	6	7	9	12
2	12	17	15	15	16
W_1	4	5	5	7	9
3	8	-12	9	9	11
4	3	4	4	5	8
R	6	4	3	5	19
5	47	-11	3	4	6
W_2	6	5	4	4	5

* [100 x (FICA value - AQUIFEM value)/AQUIFEM value)]

TABLE 5-4

Variation in resulting heads, between USGS flow model and AQUIFEM for test problem

Observation Point	% Difference in Heads*				
	t = 300 days	t = 600	t = 1200	t = 1800	t = 2700
1	-19	-14	-13	-11	-9
2	38	0	0	-3	0
W_1	8	6	5	4	3
3	-5	25	-6	-7	-6
4	1	7	-8	-7	-7
R	8	6	12	46	-51
5	-100	43	-6	-8	-7
W_2	11	8	6	3	2

* [100 x (USGS value - AQUIFEM value)/AQUIFEM value)]

GEOFLOW

Two tests were performed to assess the efficiency and accuracy of the transport portion of GEOFLOW. The first one simulated a one-dimensional flow field with two-dimensional transport, and the second simulated a two-dimensional flow field with two-dimensional transport. In both situations the flow field was time invariant. Additional details of the tests may be found in Appendix D.

The first example was configured to compare with the analytic solution of a finite source strip of pollutant in an infinite flow field. The finite element grid consists of 171 elements and 200 nodes. A known velocity of 2 ft/day is prescribed in the positive x-direction. The known input is equivalent to a strip source of concentration 1.0 with a length 60 ft, symmetrical about the line y = 200 ft. The dispersion coefficients were 80 ft^2/day in the x-direction and 20 ft^2/day in the y-direction.

Concentrations from the analytical and finite element models are shown in Figures 5-3, 4, 5 for times of 10, 100 and 1000 days, respectively. Comparison with the analytical solution appears to be excellent. The discrepancies, which are minor, occur at small times close to the source, and at the boundaries (y = 0) for t = 1000 days. Because of the approximate nature of the finite element model, these differences are not unexpected and can be considered well within reasonable and acceptable limits.

For this example, evaluation of Pe and Co in the x-direction (the principal flow direction) reveals that Pe does not exceed 1.25 and that the maximum Co is 0.80. These are acceptable values, and the consistency in the predicted concentrations provide further evidence of accurate simulation.

In the second example, a two-dimensional steady flow field is generated as shown in Figure 5-6. Pumping of 100 m^3/day occurs at location B in a confined medium and a source of equal strength is situated at location A. A tracer with a relative concentration of 1.0 is injected continuously at the source and begins to propagate into the medium. Figure 5-7 shows concentration contours at 50 days after injection. Note the symmetry about a diagonal line from the source to the sink. In this example, the longitudinal and transverse dispersivities are of equal magnitude (50 m).

Estimates of the numerical Peclet and Courant numbers can be made in either the x- or y direction, with the result that Pe is approximately 0.10 and Co ranges approximately between 0.001 and 0.10. No analytic solution is available for comparison with the finite element prediction. The exercise serves to demonstrate the application of modeling mass transport in a two-dimensional flow field.

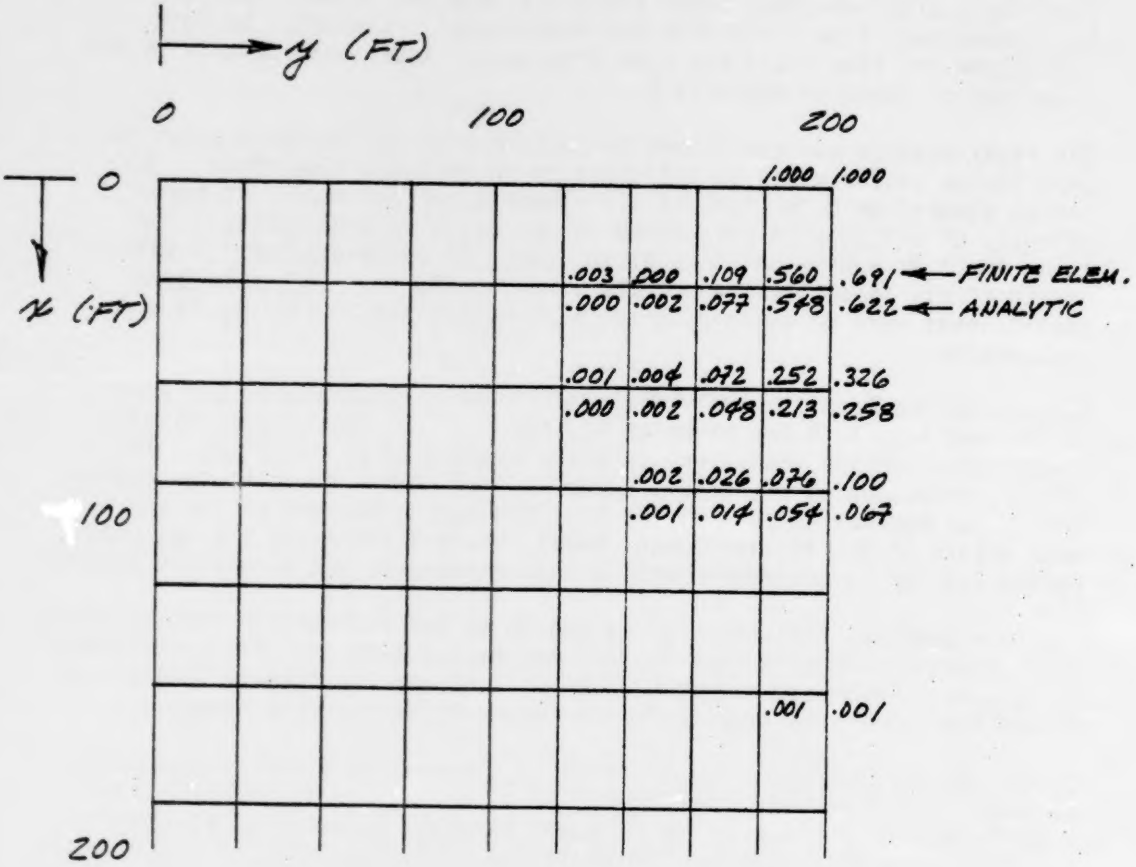

y (FT)
0
100
200
0
x (FT)
100
200
1.000 1.000
.003 .000 .109 .560 .691 ← FINITE ELEM.
.000 .002 .077 .548 .622 ← ANALYTIC
.001 .004 .072 .252 .326
.000 .002 .048 .213 .258
.002 .026 .076 .100
.001 .014 .054 .067
.001 .001

FIGURE 5-3 Finite element model of strip source; comparison with analytical model. Nodal concentrations at t = 10 days.

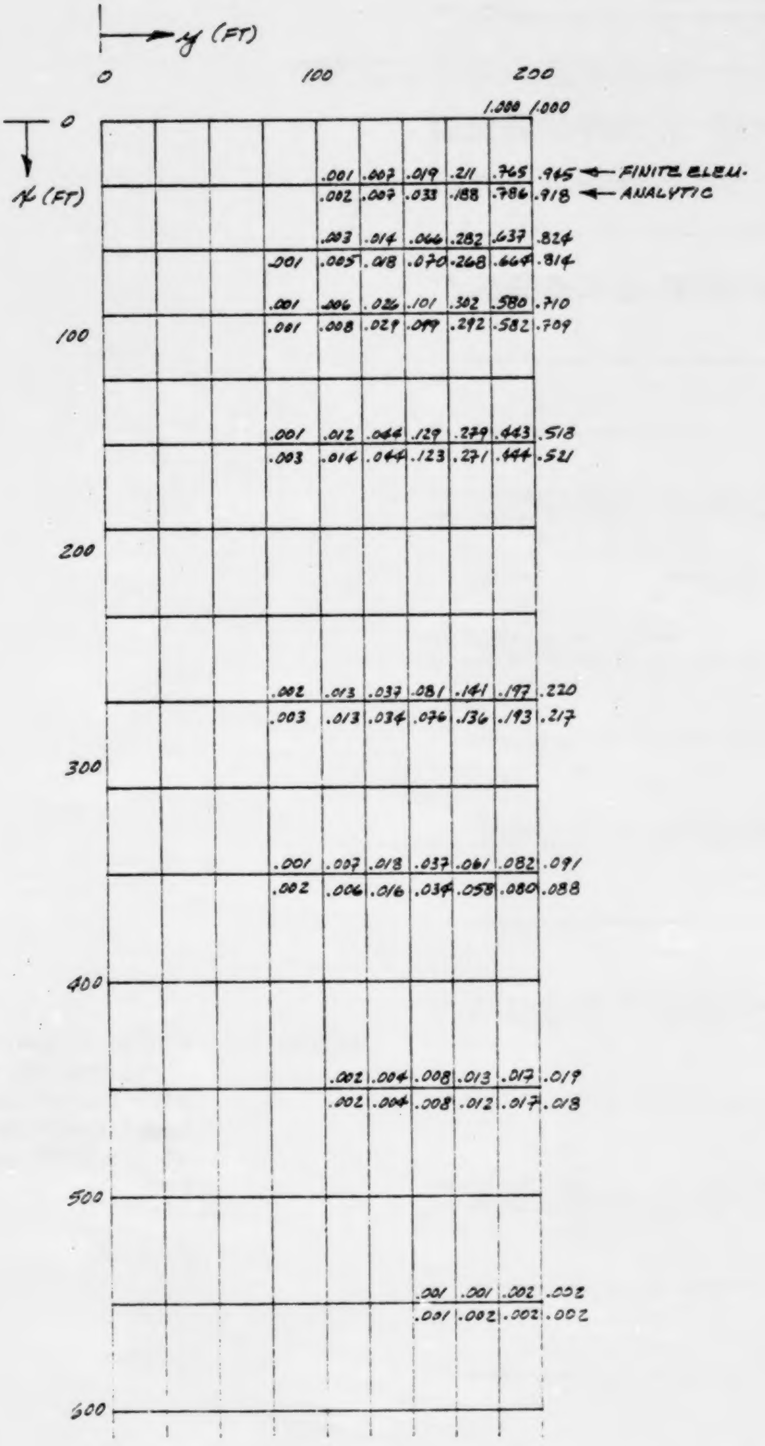

y (FT)
0
100
200
x (FT)
0
100
200
300
400
500
600
1.000 1.000
.001 .007 .019 .211 .765 .945 ← FINITE ELEM.
.002 .007 .033 .188 .786 .918 ← ANALYTIC
.003 .014 .066 .282 .637 .824
.001 .005 .018 .070 .268 .664 .814
.001 .006 .026 .101 .302 .580 .710
.001 .008 .029 .099 .292 .582 .709
.001 .012 .044 .129 .279 .443 .518
.003 .014 .044 .123 .271 .444 .521
.002 .013 .037 .081 .141 .197 .220
.003 .013 .034 .076 .136 .193 .217
.001 .007 .018 .037 .061 .082 .091
.002 .006 .016 .034 .058 .080 .088
.002 .004 .008 .013 .017 .019
.002 .004 .008 .012 .017 .018
.001 .001 .002 .002
.001 .002 .002 .002

FIGURE 5-4 Finite element model of strip source, comparison with analytical model. Nodal concentrations at t = 100 days.

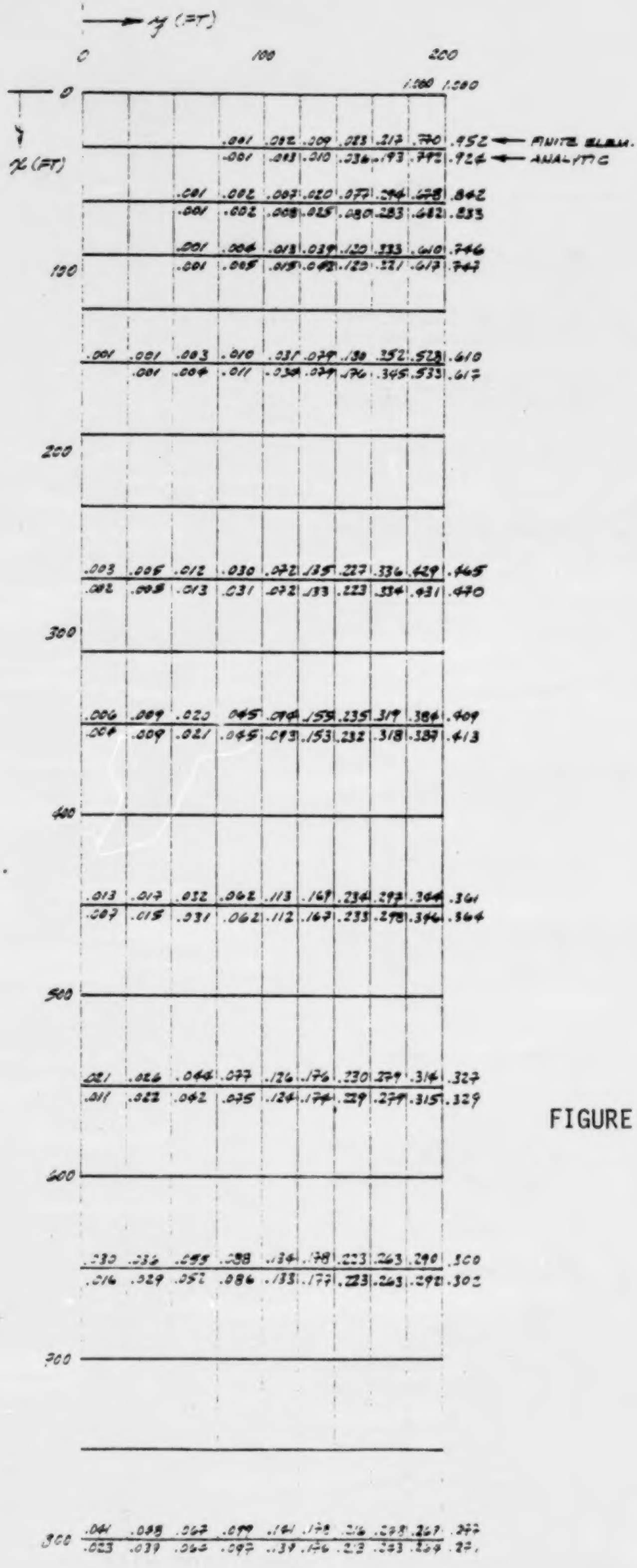
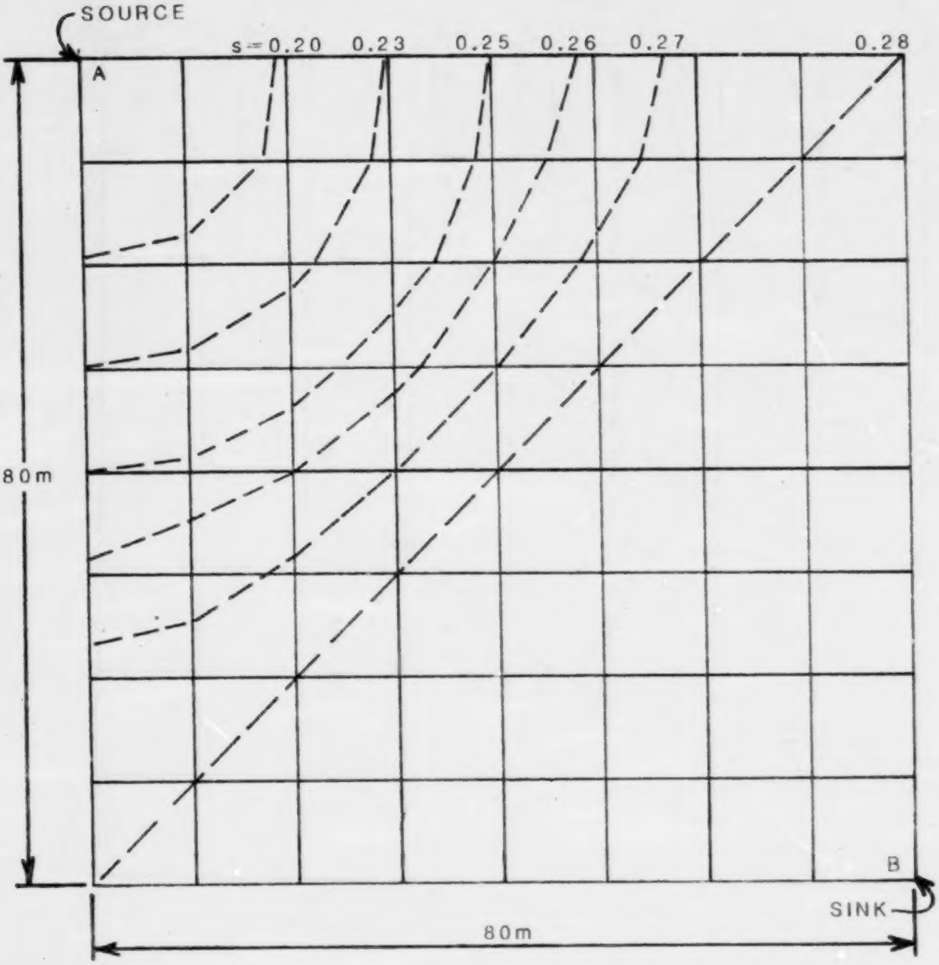

y (FT)
0
100
200
1.000 1.000
0
x (FT)
.001 .002 .009 .033 .217 .770 .952 ← FINITE ELEM.
.001 .003 .010 .036 .193 .792 .924 ← ANALYTIC
.001 .002 .007 .020 .077 .294 .678 .842
.001 .002 .008 .025 .080 .283 .682 .833
.001 .004 .013 .039 .120 .333 .610 .746
.001 .005 .015 .042 .129 .321 .617 .747
100
.001 .001 .003 .010 .031 .079 .180 .352 .528 .610
.001 .004 .011 .034 .079 .176 .345 .533 .617
200
.003 .005 .012 .030 .072 .135 .227 .336 .429 .465
.002 .005 .013 .031 .072 .133 .223 .334 .431 .470
300
.006 .009 .020 .045 .094 .159 .235 .319 .384 .409
.004 .009 .021 .045 .093 .153 .232 .318 .387 .413
400
.013 .017 .032 .062 .113 .169 .234 .297 .344 .361
.007 .015 .031 .062 .112 .167 .233 .298 .346 .364
500
.021 .026 .044 .077 .126 .176 .230 .279 .314 .327
.011 .022 .042 .075 .124 .174 .229 .279 .315 .329
600
.030 .036 .055 .088 .134 .178 .223 .263 .290 .300
.016 .029 .052 .086 .133 .177 .223 .263 .290 .302
700
800
.041 .048 .067 .099 .141 .179 .216 .238 .267 .277
.023 .039 .064 .097 .139 .176 .213 .243 .264 .27

FIGURE 5-5 Finite element model of strip source, comparison with analytical model. Nodal concentrations at t = 1000 days.


SOURCE
s = 0.20
0.23
0.25
0.26
0.27
0.28
A
B
80m
80m
SINK

$T_{11} = T_{22} = 900 \text{ m}^2/\text{day}$

$\alpha_L = \alpha_T = 50 \text{ m}$

$n_e = 0.25$

$P = 100 \text{ m}^3/\text{day}$

FIGURE 5-[illegible] Finite element model of two-dimensional flow field.

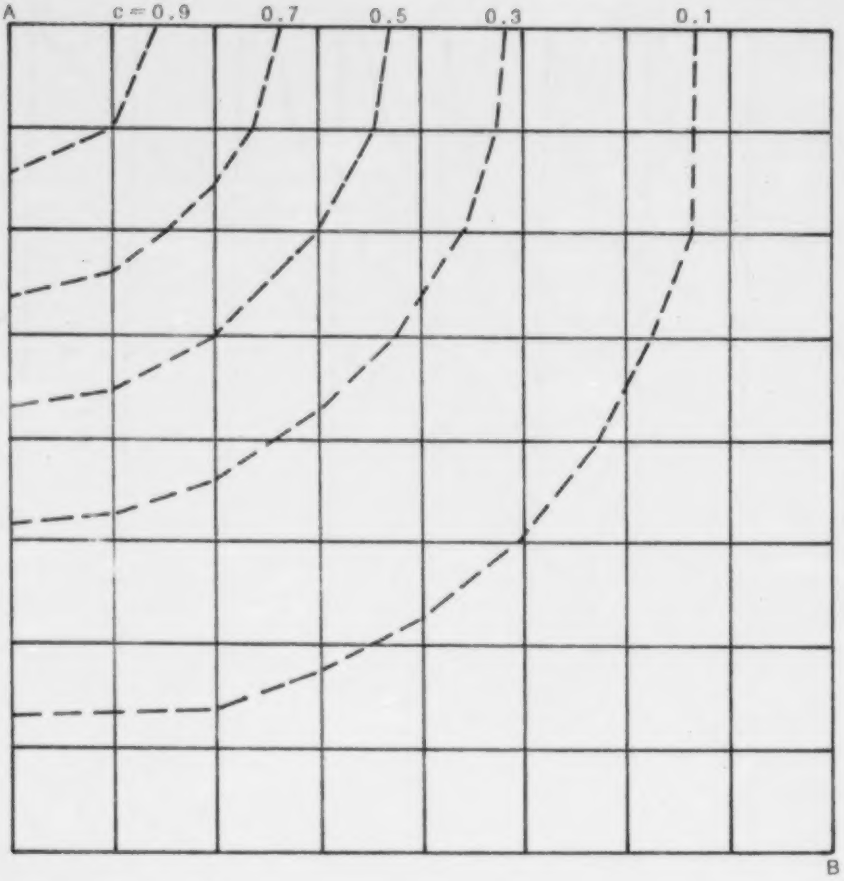


FIGURE 5-7 Concentration contours 50 days after start of injection. Time step = 0.5 day.

The two examples presented in this section reveal that accurate and practical numerical predictions of mass transport can be made with the finite element model GEOFLOW. This is to be expected since the Pe and Co criteria have been satisfied in the example problems. Further examples, including analytical verification, are provided in D'Appolonia (1980).

USGS Mass Transport Model

The USGS Mass Transport Model was tested against one of Cleary and Ung's two-dimensional analytical mass transport models. A uniform groundwater flow field of 2 ft/day was simulated with a 25 foot wide constant source at one upstream side of the system. An element size of 25' x 50' was used in the USGS model. The computed results are compared with an analytical solution to the same problem 100 days after the beginning of the source in Figure 5-8. The comparisons are quite good except near the source. This is due to the fact that the USGS model distributes sources over entire elements, and also partially due to the fact that concentrations are averaged over nodes. The only way to improve the simulation is to use a finer grid. There does not appear to be a problem with numerical dispersion and none is expected with the Method of Characteristics formulation.

There is a bit of a problem in interpreting the USGS results. It appears that the model values should be plotted at the center of the element for best comparison with the analytical solution. For situations where the contamination begins at $t = 0$, the source node should be initialized at the source concentration value.

These tests do not represent a complete verification of the models. They were intended to expose some potential problems, and allow the users to gain experience and confidence in operating the models.

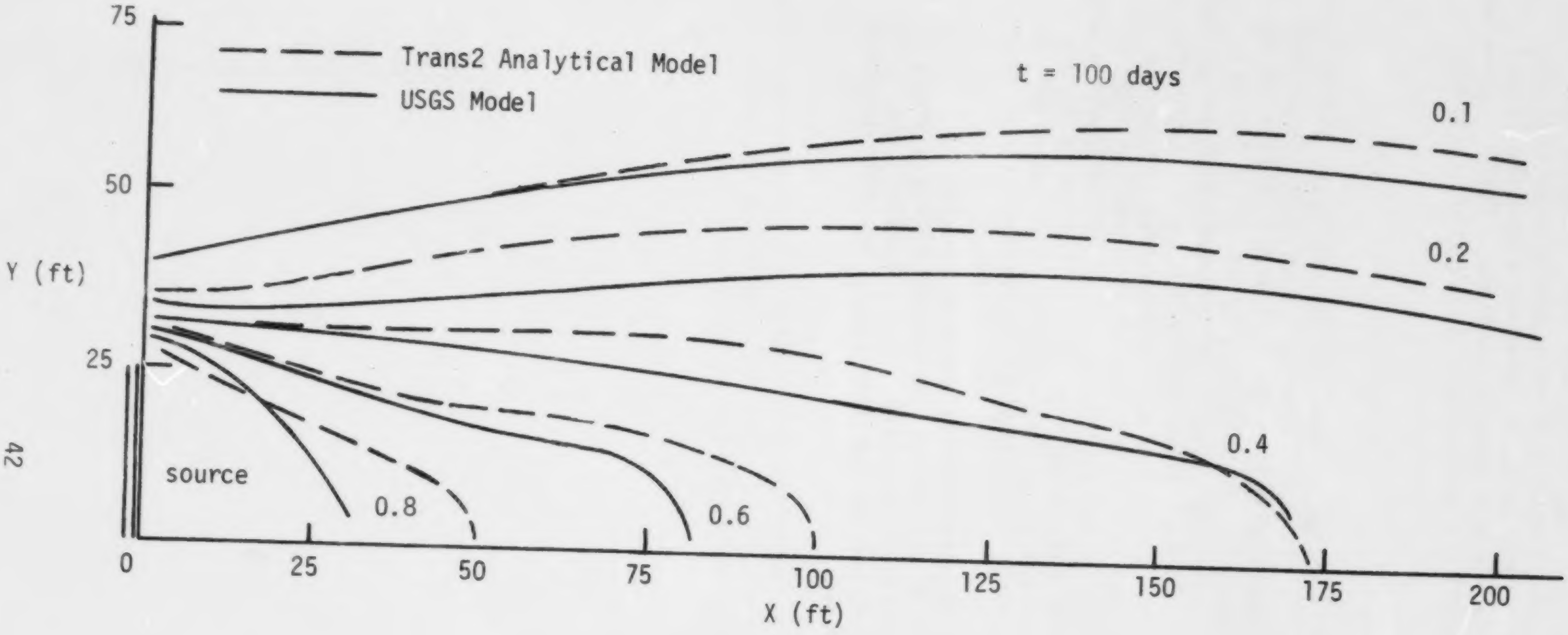


FIGURE 5-8 Comparision of Analytical results with USGS model computations for an instantaneous strip source. The lines represent relative concentration contours (C/C_o).

SECTION IV

CASE STUDIES

CHAPTER 6

SOUTHWEST OTTAWA COUNTY LANDFILL

Southwest Ottawa County Landfill opened in 1968. It is located about 1 1/2 miles from Lake Michigan, north of Holland (see Figure 6-1). The soil near the site is principally coarse sand, characteristic of much of Michigan's western coast. It is very permeable and readily transmits landfill leachate. Leachate has entered the aquifer, creating a contaminant plume that extends more than 1/2 mile from the site. The plume has impacted some private wells and is approaching others (see Figure 6-2). Aromatic hydrocarbons, some metals and various inorganic compounds have been found in the aquifer. Some example concentrations are: benzene 120 ppb, chromium 6 ppb, and chlorides 350 ppm. There are many contaminant plumes eminating from the site. Different materials were obviously dumped there at different times. The aquifer has been the sole water supply source for residents near the site. The DNR wants measures taken to prevent future contamination, and the present contamination cleaned up.

Plans for clean up are complicated by the presence of low permeability lenses. These lenses affect the flow patterns and movement of the contaminant plume. They would also influence the effectiveness of a purge well system.

A model of the site was developed to allow evaluation of proposed purge well system designs and determine which is likely to be most effective in meeting management objectives.

The model realistically simulates the known aquifer behavior. Predictions of how the aquifer will respond to different purge well systems are made. The predictions are estimates based on the known data, but they also incorporate all the known physical complexities.

Hydrogeology

Geologists from the DNR's Resource Recovery Division gathered the known geologic information and helped interpret it for use in the model. Domestic well logs did not provide much information. The domestic wells tend to be shallow stab wells, which confirm the presence of a widespread permeable water table aquifer. A groundwater investigation of the Holland area was completed by Deutsch, et al in 1958. From this and other well logs, the Resource Recovery geologists estimated that the aquifer is phreatic, and extends from near the land surface to a depth of about 90 feet. Below this an extensive clay layer exists. Deutsch, et al reported hydraulic conductivities in the area ranging from about 60 to 230 feet/day.

A hydrogeologic investigation was performed around the landfill. This provided detailed information of the soil types, depths and water table elevations. Figure 6-3 shows the monitoring well locations and the interpreted water table contours. There are distortions in the flow field south

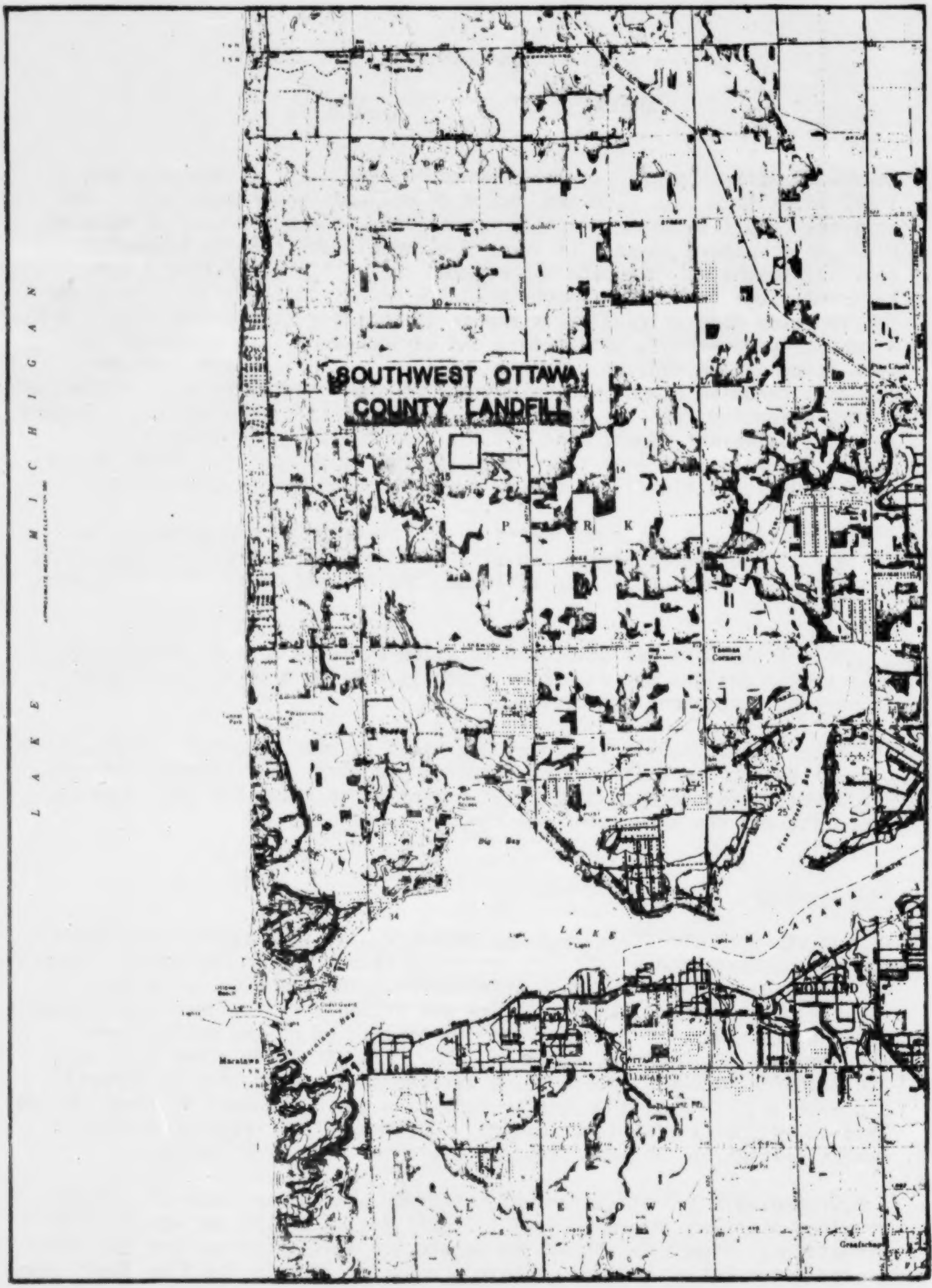
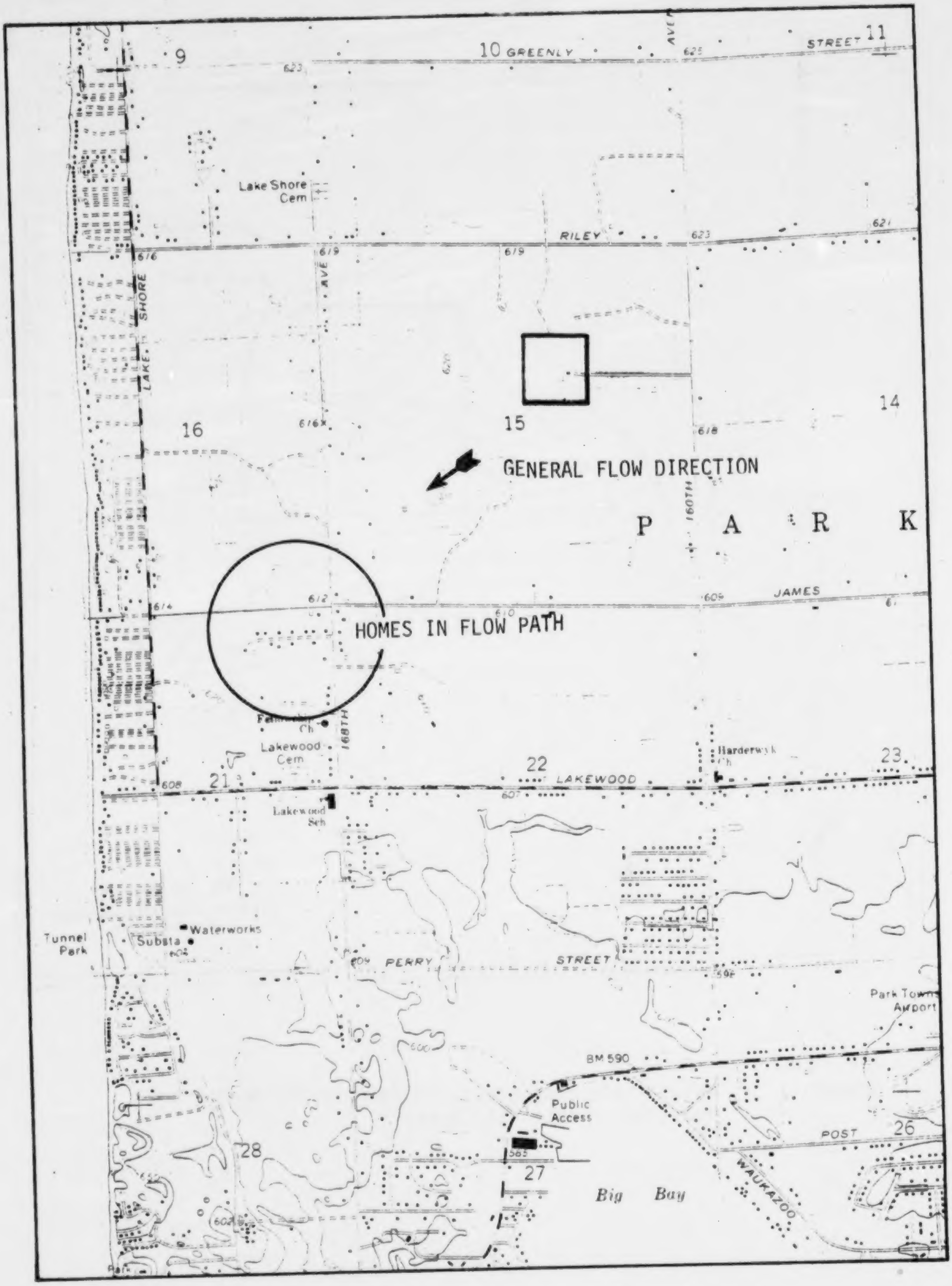

LAKE MICHIGAN
SOUTHWEST OTTAWA COUNTY LANDFILL
PARK
Big Bay
Pine Creek Bay
LAKE MACATAWA
HOLLAND
LAKETOWN
Macatawa

FIGURE 6-1 Location of Southwest Ottawa County Landfill.



9
10 GREENLY
STREET
11
623
625
Lake Shore Cem
RILEY
623
621
616
619
619
LAKE SHORE
AVE
AVE
15
14
16
616
618
GENERAL FLOW DIRECTION
160TH
P A R K
612
614
610
609
JAMES
HOMES IN FLOW PATH
Fellowship Ch
Lakewood Cem
168TH
Harderwyk Ch
22
23
21
608
LAKEWOOD
607
Lakewood Sch
Tunnel Park
Waterworks
Substa
PERRY
STREET
604
598
Park Town Airport
BM 590
600
Public Access
POST
26
28
585
27
Big Bay
WAUKAZOO
602

FIGURE 6-2 General flow direction and downstream houses.

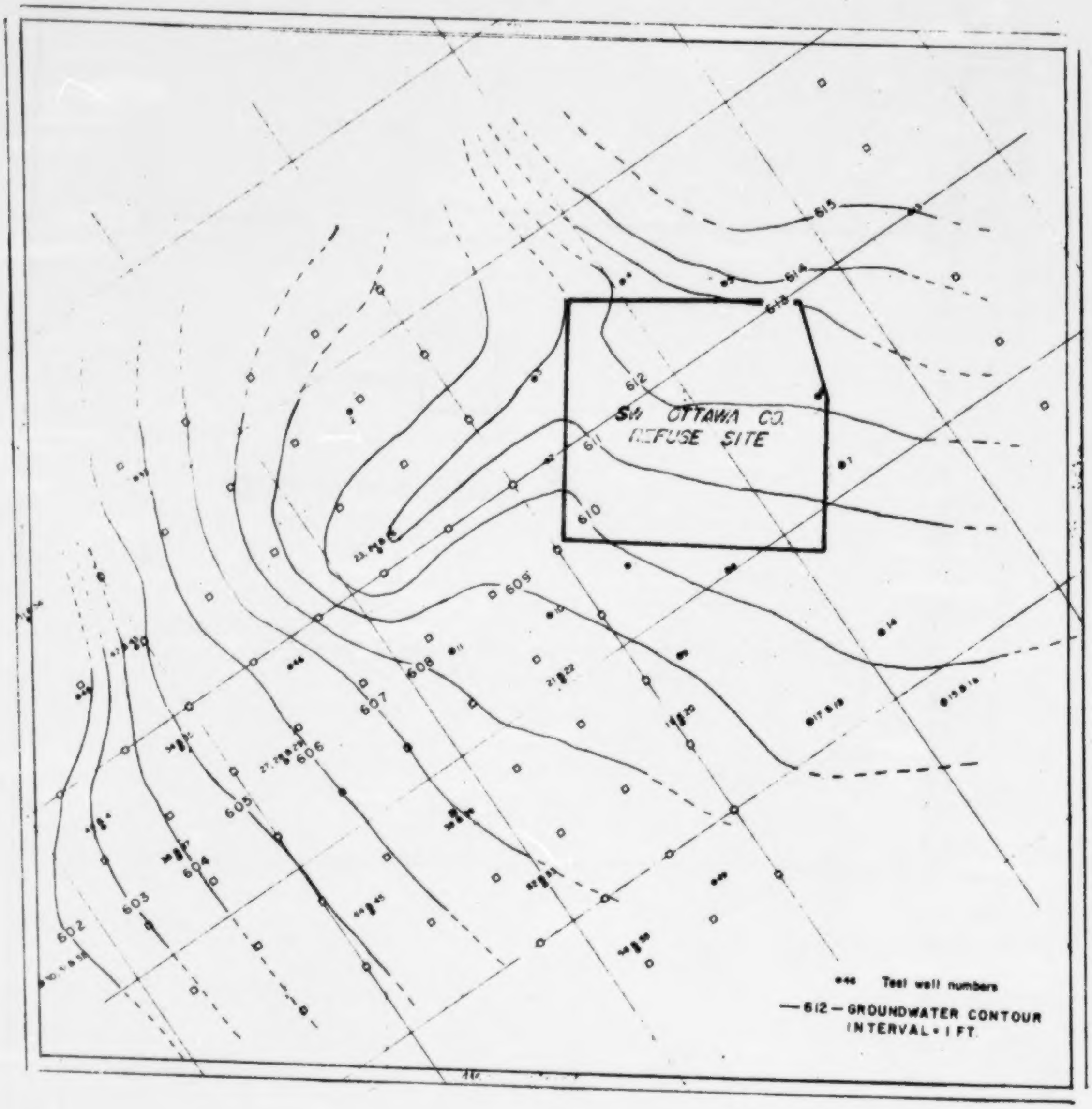

615
614
613
612
SW OTTAWA CO.
REFUSE SITE
611
610
609
608
607
606
605
604
603
602
•46 Test well numbers
612 — GROUNDWATER CONTOUR
INTERVAL = 1 FT.

FIGURE 6-3 Water table contours based on observed heads; and location of observation wells.

and west of the landfill that indicate the presence of low permeability silt and clay lenses. Soil boring data confirm this. The aquifer hydraulic conductivity was estimated to be about 3 feet/day in the hydrogeologic report. The basis of this estimate is not clear.

Resistivity Survey

A very valuable resistivity survey of the site was conducted by Roger Noyce, a Resource Recovery geologist. Resistivity analysis is a technique by which the relative electrical conductivities at various depths are measured from the ground surface. A general description of resistivity surveys can be found in a text such as Griffiths and King (1975). Resistivity analysis is usually done to try to locate different geologic formations, which is possible because of differences in electrical conductivity. Contaminants in a plume make it more conductive than the surrounding uncontaminated groundwater. Resistivity analysis can then be used to outline the plume, both areally and with depth. This provides much more information than can be obtained from many borings, although it is still necessary to have borings and monitoring wells to confirm and calibrate the resistivity results.

The plume outline at three depths as determined by the resistivity survey is presented in Figures 6-4 to 6-6. The resistivity survey results were correlated with water samples taken at different depths from "nested" monitoring wells and the well logs. A very beneficial result of this survey is not only outlining the areas that have been contaminated, but also those that have not. This is important because the areas that the plume has obviously diverted around are the lenses of low permeability. Thus a detailed description of the lenses' shapes and depths became available. This greatly increased the ability to create a model that realistically includes the complexities of the aquifer system.

Model Goal & Approach

A computer model is needed to assist in evaluating the effects of the low permeability silt and clay lenses. The lenses can complicate the interpretation of field data, and the design of a purge well system. A conceptual model cannot yield the quantification needed for design purposes, and traditional analytical techniques cannot handle the complex boundary conditions. *The model goal is to develop a model that reasonably represents the site geology and can be used to interpret future pump test data and evaluate the effectiveness of proposed purge well systems.*

After reviewing the available data and establishing the model goals, the modeling approach was determined. Many different contaminants are involved. They can have different adsorption characteristics, and they have entered the aquifer at different times over a period of years. The overall plume

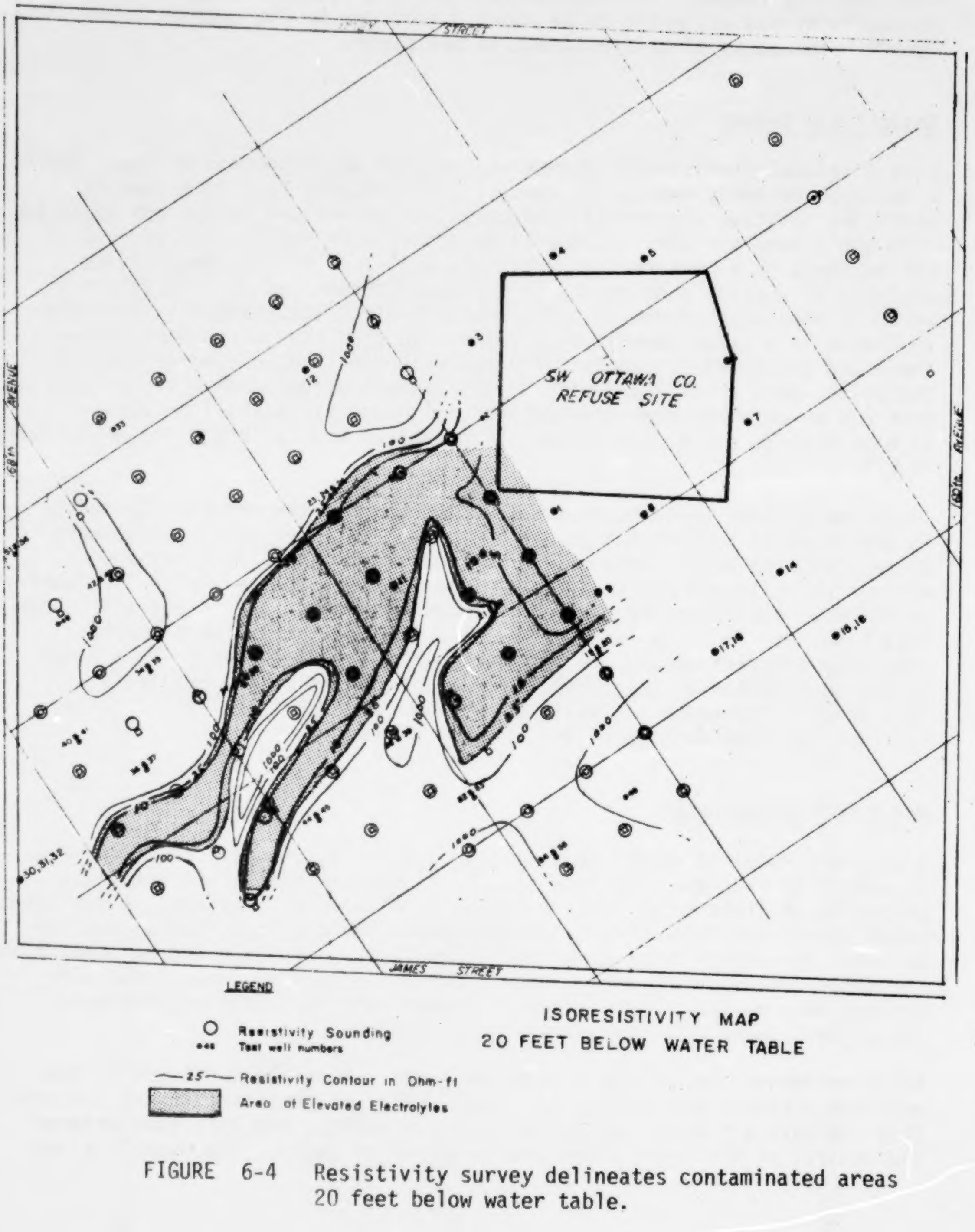

STREET
68th AVENUE
SW OTTAWA CO.
REFUSE SITE
100th AVENUE
JAMES STREET
1000
100
25
10
4
5
3
12
33
7
8
14
17,18
15,16
30,31,32
LEGEND
Resistivity Sounding
Test well numbers
25 Resistivity Contour in Ohm-ft
Area of Elevated Electrolytes
ISORESISTIVITY MAP
20 FEET BELOW WATER TABLE

FIGURE 6-4 Resistivity survey delineates contaminated areas 20 feet below water table.

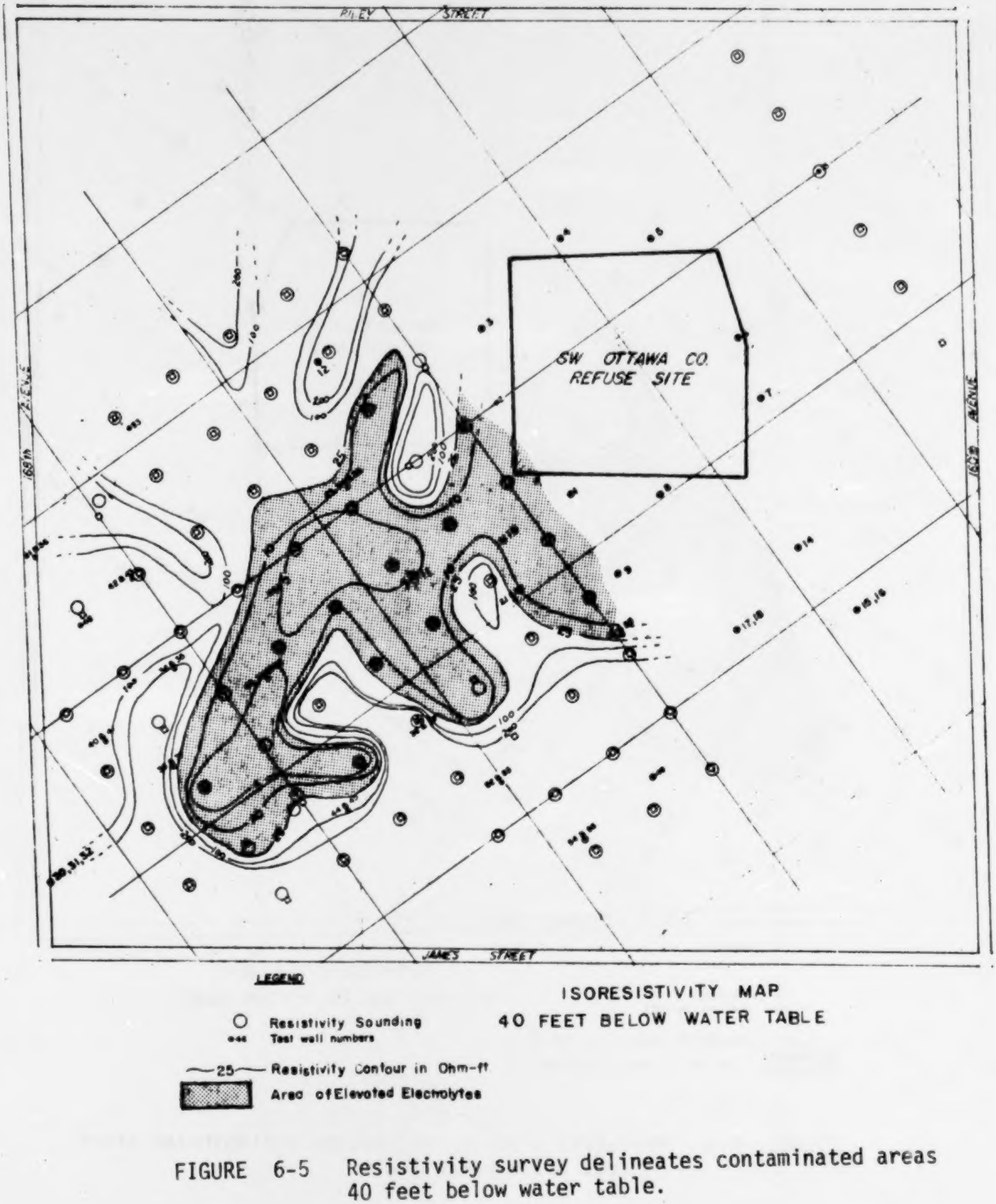

RILEY STREET
SW OTTAWA CO. REFUSE SITE
168th AVENUE
160th AVENUE
JAMES STREET
25
100
200
LEGEND
○ Resistivity Sounding
Test well numbers
—25— Resistivity Contour in Ohm-ft
Area of Elevated Electrolytes
ISORESISTIVITY MAP
40 FEET BELOW WATER TABLE

FIGURE 6-5 Resistivity survey delineates contaminated areas 40 feet below water table.

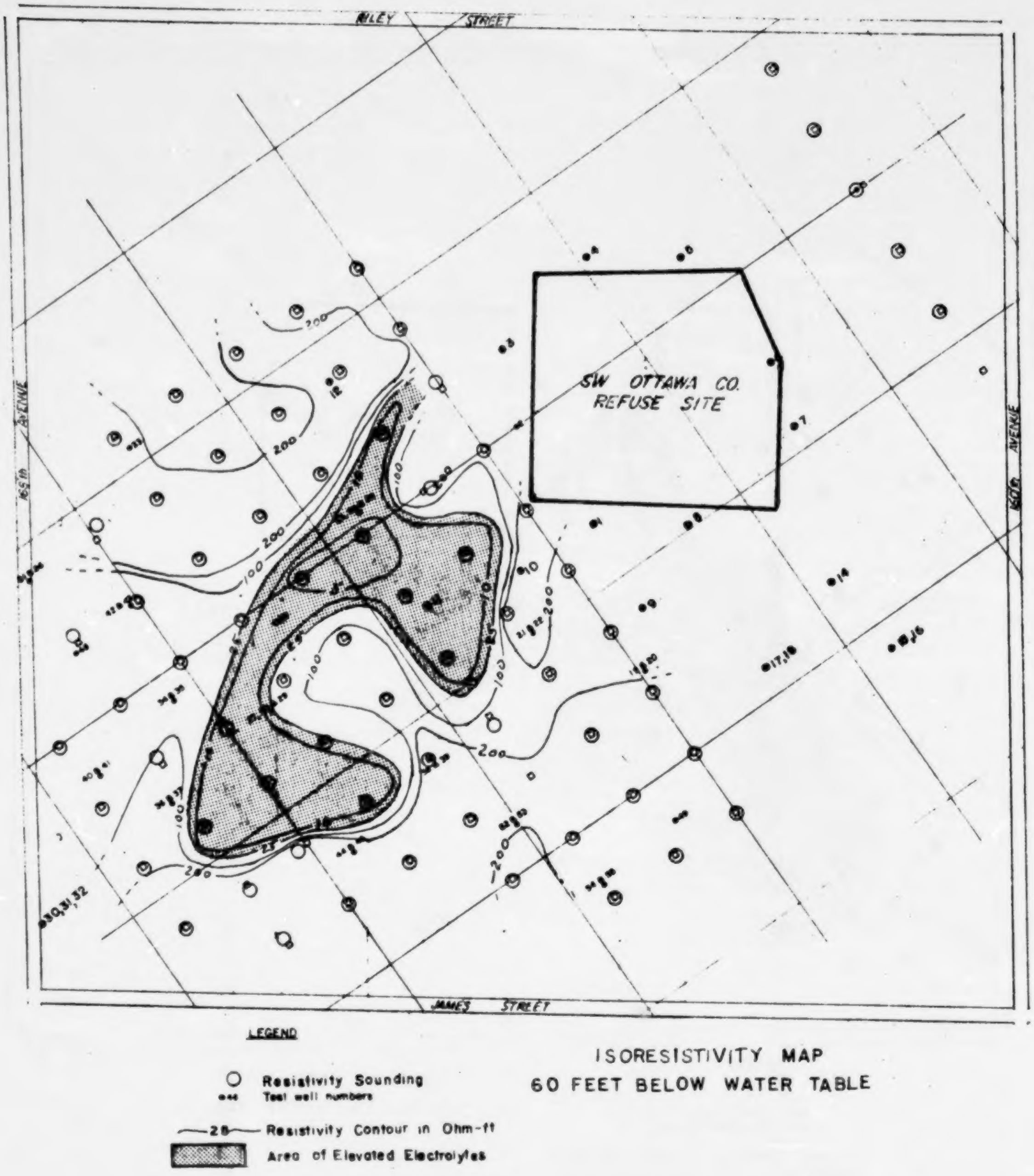

RILEY STREET
JAMES STREET
168th AVENUE
160th AVENUE
SW OTTAWA CO. REFUSE SITE
200
100
25
LEGEND
Resistivity Sounding
Test well numbers
Resistivity Contour in Ohm-ft
Area of Elevated Electrolytes
ISORESISTIVITY MAP
60 FEET BELOW WATER TABLE

FIGURE 6-6 Resistivity survey delineates contaminated areas 60 feet below water table.

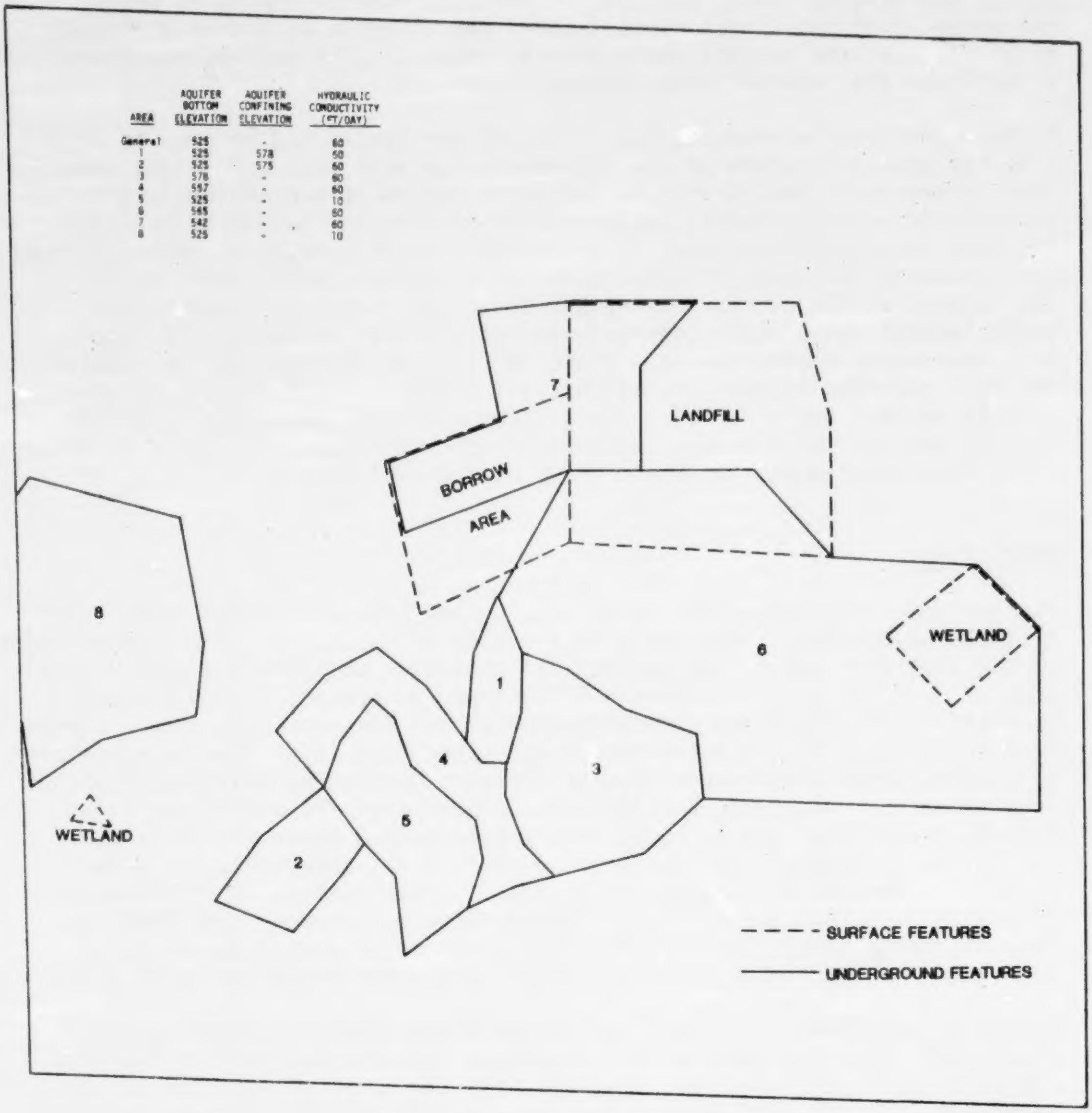
is a complicated assortment of contaminants, with varied and unknown source conditions. There would be little advantage in trying to track the movement of individual contaminants, and it would be a very difficult task. To meet the project goals at this stage it will only be necessary to evaluate the problem hydraulically.

A flow model can incorporate the effect of the lenses and be used to determine the zone of capture of any proposed purge well systems. Since some three-dimensional information is available and there are obviously some 3-D effects in the problem, there is a temptation to try and fully model the site in three dimensions. However, this would likely be over ambitious. The saturated thickness of the aquifer is relatively small compared to the lateral extent of the aquifer and the plume travel distance. This small "aspect ratio" is a generally accepted indicator that a 2-D model is a reasonable approximation. Since there is no current need to simulate the full 3-D flow through the lenses, a 2-D model should be able to adequately reflect the flow field distortions caused by the lenses. If the results are not satisfactory, a 3-D model can still be investigated. Hence a 2-D flow model meets the basic needs of the project.

Model Input

The geologic information had to be interpreted and schematized into a form that can be modeled. This requires a number of assumptions and extrapolation of the available data. The geologists' expertise was combined with a knowledge of modeling capabilities and limitations to produce a complete and realistic, yet simplified interpretation of all the available data. Lenses near the surface were assumed to act as a confining layer down to a certain elevation, those located near the bottom were handled by assigning a higher aquifer bottom elevation, and those that penetrated the entire saturated thickness were assigned a corresponding area with a lower hydraulic conductivity. A general aquifer bottom elevation was determined, as were initial estimates of recharge and hydraulic conductivity. Possible areas of special interest were also delineated, such as a swampy area that may be a discharge point, and a borrow area under which a groundwater mound has formed. These areas and the various lenses are shown in Figure 6-7.

Boundary conditions can have a very significant effect on model results. A regional model was made to help determine the most appropriate boundary conditions and parameters for the more detailed local model. Two of the boundaries for the regional boundary are readily determined--Lake Michigan and Lake Macatawa. These are specified head boundaries. For the other boundaries it would be convenient to determine no flow boundaries along streamlines. At some point to the north, the streamlines should be due west toward Lake Michigan. East of the landfill the surface drainage is southerly. Because of the influence of Lake Macatawa to the south, and the surface drainage, it seems likely that there is a southern streamline. These streamlines were estimated and delineated on a topographic map (Figure 6-8). A sensitivity analysis of the boundaries was later performed.



AREA	AQUIFER BOTTOM ELEVATION	AQUIFER CONFINING ELEVATION	HYDRAULIC CONDUCTIVITY (FT/DAY)
General	525	-	60
1	525	578	50
2	525	575	60
3	578	-	60
4	557	-	60
5	525	-	10
6	565	-	60
7	542	-	60
8	525	-	10

7
LANDFILL
BORROW
AREA
8
6
WETLAND
1
4
3
5
2
WETLAND
SURFACE FEATURES
UNDERGROUND FEATURES

FIGURE 6-7 Features incorporated into local model.

With these boundaries, the only recharge to the aquifer is from rainfall infiltration and percolation to the groundwater table. This is a very difficult parameter to estimate. Studies that have been submitted to the DNR in sandy areas like this have used a range of values. The values tend to be educated estimates or possibly parameters used in model calibration. Keck Consulting Services in a study of Story Chemical (Muskegon County) used a recharge rate of 10.5 inches/year. The U.S. Geological Survey (USGS) used 15 inches/year at Wurtsmith Airforce Base (Iosco County). Other USGS studies have indicated that recharge rates greater than 18 inches/year are possible in glacial outwash deposits. Another possible indicator is average annual streamflow. In very sandy basins, relatively little of the streamflow is directly contributed by surface runoff. Most of the flow is expected to be contributed by base flow, the discharge from the aquifer system. A review of streamflow records from the Black, Boardman, Pine, and White rivers revealed a range of annual discharges between 12 and 17 inches/year. Three of the stations were over 15 inches/year.

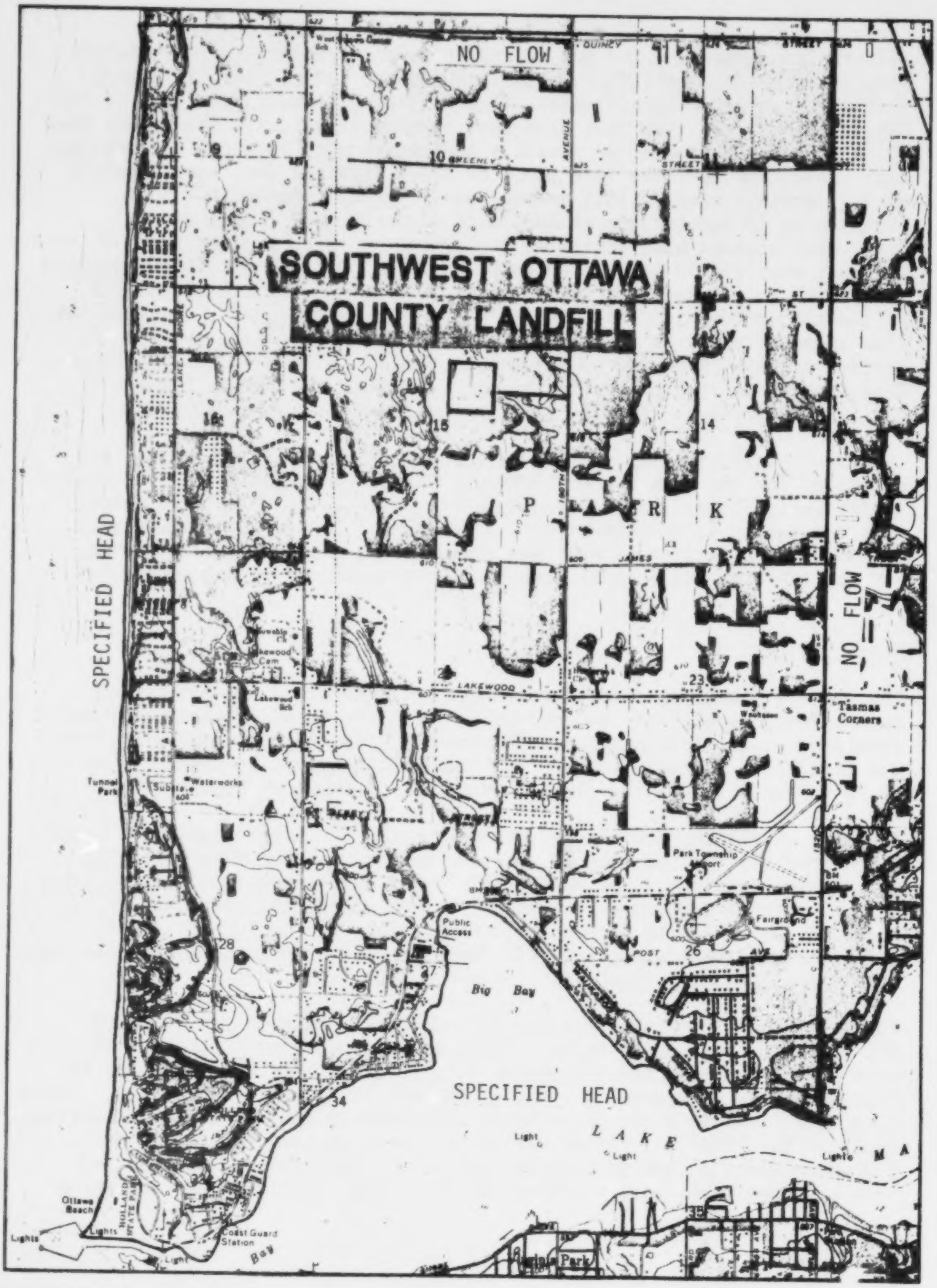
Considering all this information, a recharge rate of 13 inches/year was estimated for the area around Southwest Ottawa County Landfill. A sensitivity analysis was eventually done with this parameter, but the initial work maintained it as a constant. A horizontal aquifer bottom was also assumed. An elevation of 525' was assigned based on the geologic data. For the regional scale model, the aquifer was assumed to be homogeneous.

Model Calibration

The value of the hydraulic conductivity was determined by calibrating the regional model, i.e. the hydraulic conductivity was varied until the simulated piezometric heads were reasonably close to measured values near the landfill. A reasonable fit was made with a hydraulic conductivity of 70 ft/day. The finite element grid used is shown in Figure 6-9.

Boundary conditions and initial parameters for the local model were determined from the regional model. No flow boundaries were made following streamlines, and specified head boundaries along piezometric contour lines at the upstream and downstream edges. These boundaries are shown in Figure 6-10. A finite element grid was designed to include a lot of detail around the low permeability lenses and incorporate all the boundary conditions previously described (Figure 6-11).

Boundary conditions were adjusted in the initial runs to try to match the observed piezometric heads. Recharge was increased in the borrow area to try to reproduce the mound. Ground elevations were adjusted in the swampy area. Hydraulic conductivity was adjusted in the lenses. Field data were reexamined and adjustments were made to aquifer bottom elevations south of the landfill. After making all these changes, there was still a problem matching the groundwater contours. Furthermore, the revised boundary conditions were starting to affect the solution. For one thing


NO FLOW
SOUTHWEST OTTAWA COUNTY LANDFILL
SPECIFIED HEAD
NO FLOW
SPECIFIED HEAD
P A R K
QUINCY
GREENLY
AVENUE
STREET
JAMES
LAKEWOOD
POST
AVE
Tasmas Corners
Tunnel Park
Waterworks
Park Township Airport
Fairground
Public Access
Big Bay
Light
LAKE MA
Ottawa Beach
HOLLAND STATE PARK
Coast Guard Station
Lights
Bay
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14
15
16
23
26
27
28
34

FIGURE 6-8 Initial boundaries used in regional model.

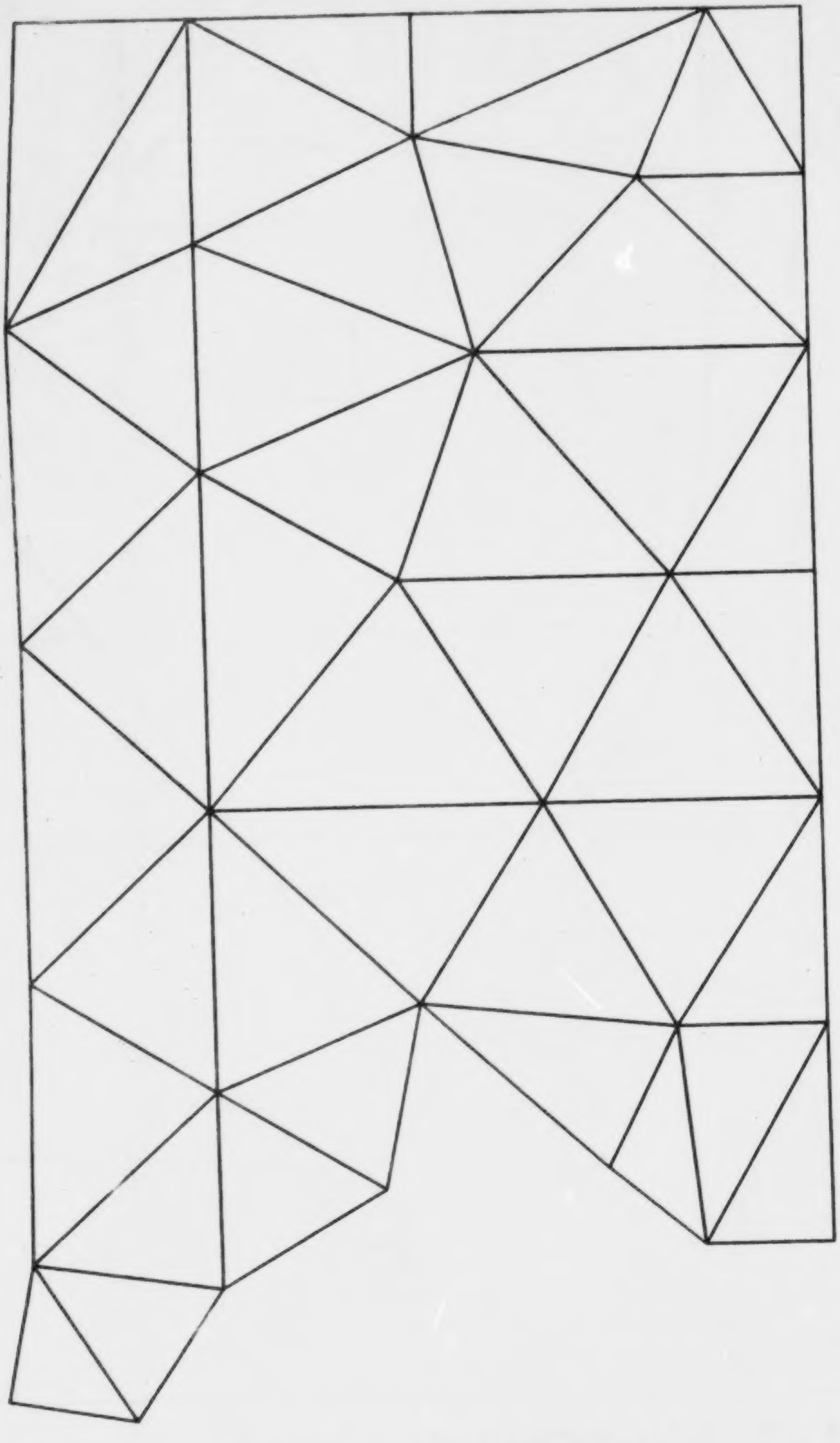
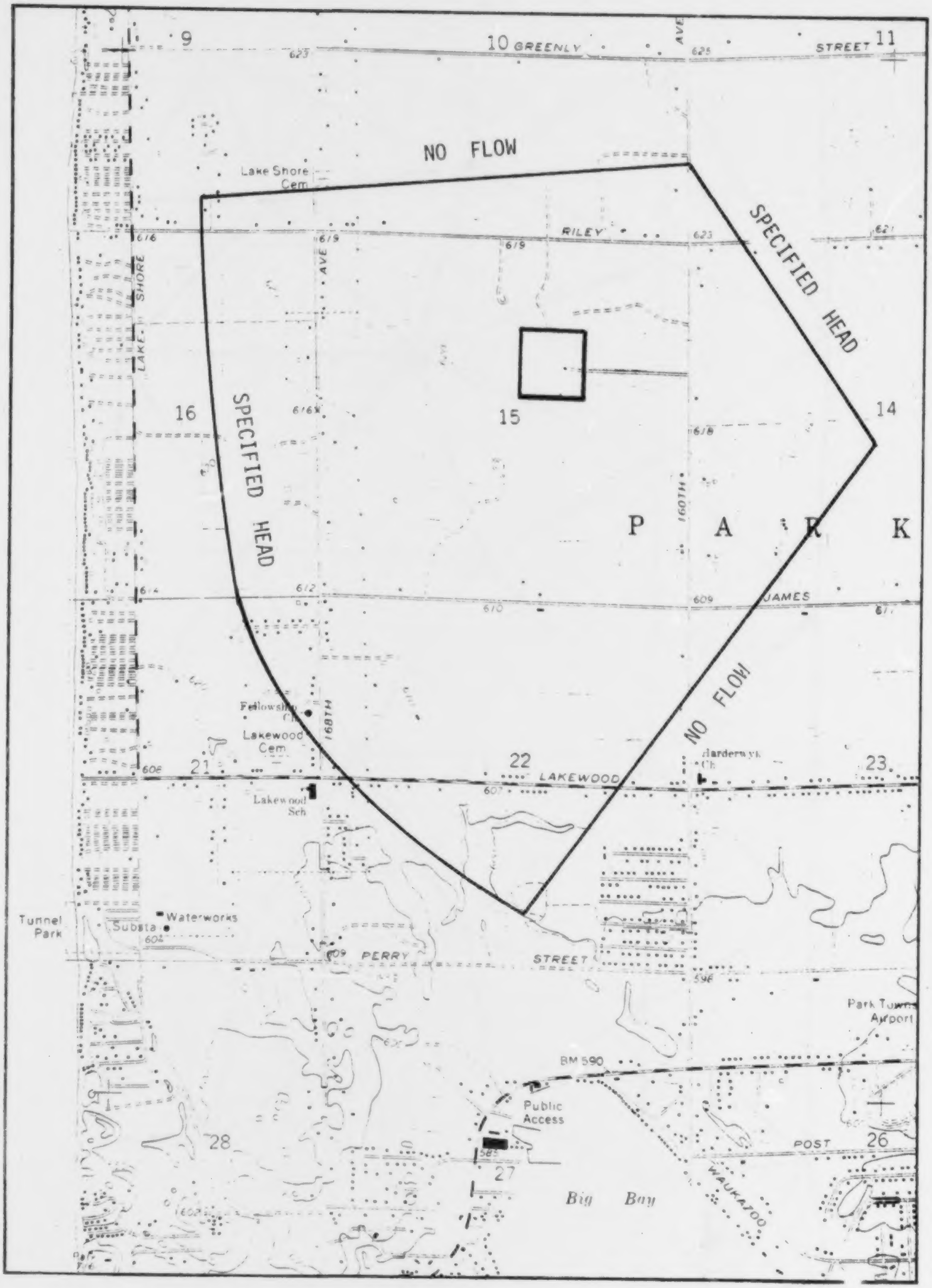


FIGURE 6-9 Initial regional finite element grid.


NO FLOW
SPECIFIED HEAD
SPECIFIED HEAD
NO FLOW
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GREENLY
STREET
RILEY
JAMES
LAKEWOOD
PERRY
STREET
POST
WAUKAZOO
LAKE SHORE
AVE
168TH
160TH
P A R K
Lake Shore Cem
Fellowship Ch
Lakewood Cem
Lakewood Sch
Harderwyk Ch
Tunnel Park
Waterworks
Substa
Public Access
Park Towns Airport
BM 590
Big Bay

FIGURE 6-10 Initial boundaries used in local model.

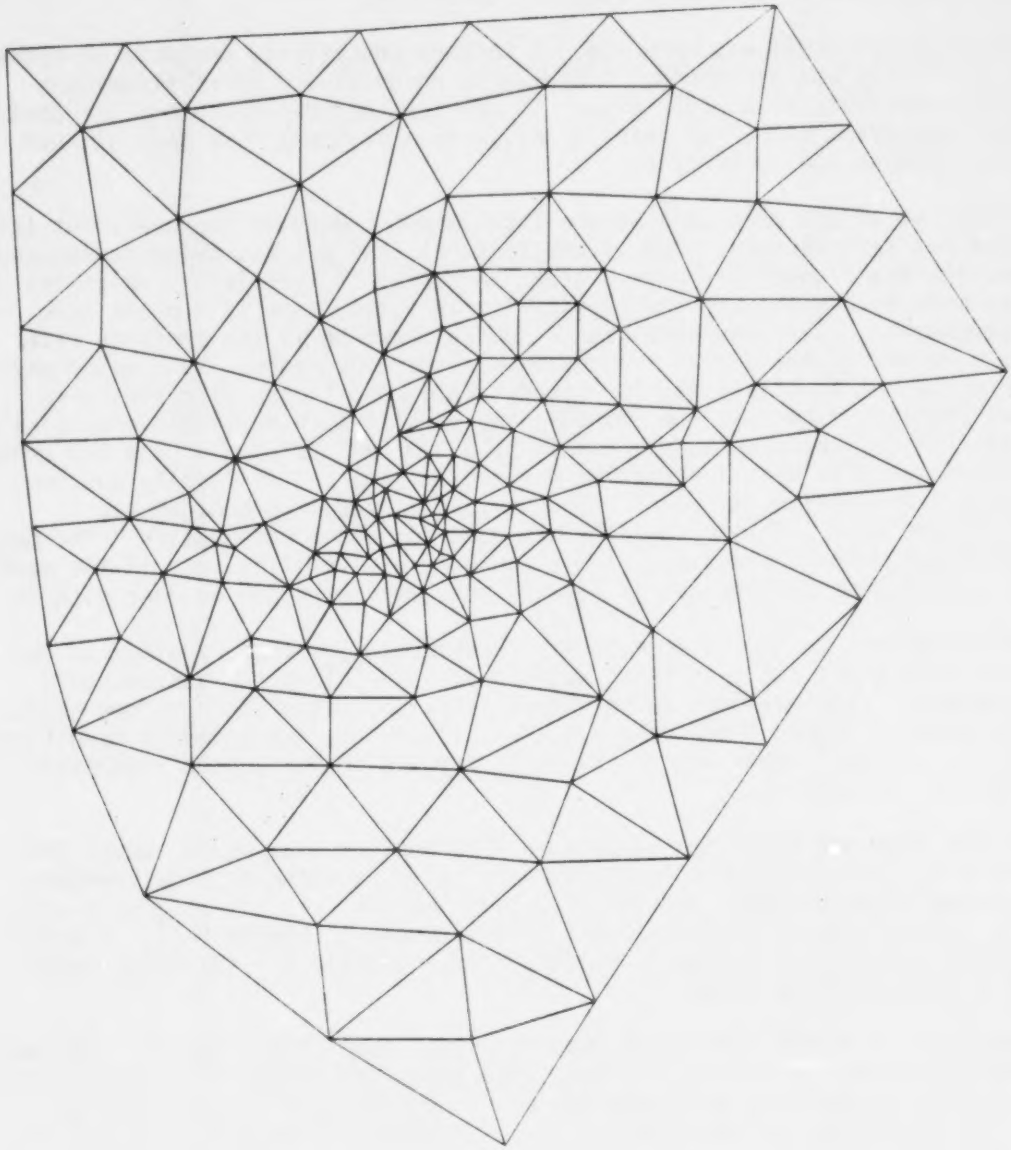

FIGURE 6-11 First finite element grid for local model.

the swamp area was being forced to withdraw an unreasonable amount of water from the system; it became clear that its influence had been overrated and that there must be some more dominant boundary condition. Therefore, it was decided to try the regional model again and determine if there was a more reasonable boundary condition.

The regional model was again run. A refined sensitivity analysis of hydraulic conductivity was performed. A hydraulic conductivity of 65 ft/day was most compatible with field data. It was also decided to change the upstream and downstream specified heads to allow an additional five feet of head loss through the local grid.

These new values were used in the local model. Results improved, but still were not satisfactory. One of the features that was not being reproduced was the mound under the borrow area. A series of transient simulations was made to investigate the possibility that the mound is a short term phenomenon. There may have been a sudden increase in the recharge rate as a result of the abrupt changes in surface topography. So a mound may form but not be maintained for steady state conditions. The runs were not conclusive because the mounding may involve such vertical velocities that can only be examined in detail by a 2-D vertical model or a 3-D model. The piezometric head information was reexamined, and vertically averaged as in a 2-D horizontal model. The revised piezometric contour map is in Figure 6-12 This became the map used for model calibration. The mound was assumed to be transient. This can be field verified, and if the mound is a permanent feature and is significant, more work can be done with it.

Major changes in the local boundary conditions were made by altering the specified heads and specifying additional heads along the southwestern boundary. This was done in an effort to better match the observed heads. The results looked promising, but were "forced" by the boundary conditions. So the regional model was run again to try and identify more reasonable boundary conditions.

In the regional model the eastern no flow boundary was moved toward the landfill. Two different locations were tried, and the no flow boundary located along the east section line gave the best results (Figure 6-13). The final regional finite element grid is shown in Figure 6-14. A sensitivity analysis of hydraulic conductivity indicated K = 40 ft/day would be a good starting value.

The local grid was rearranged into its final form (Figure 6-15). The model was calibrated by varying the specified heads and hydraulic conductivities. Sensitivity analyses were made for each. *A hydraulic conductivity of 60 ft/day proved to have the best fit. Recharge rates of 11, 13 and 15 inches/year were then simulated. It was decided to continue using 13 inches/year recharge.*

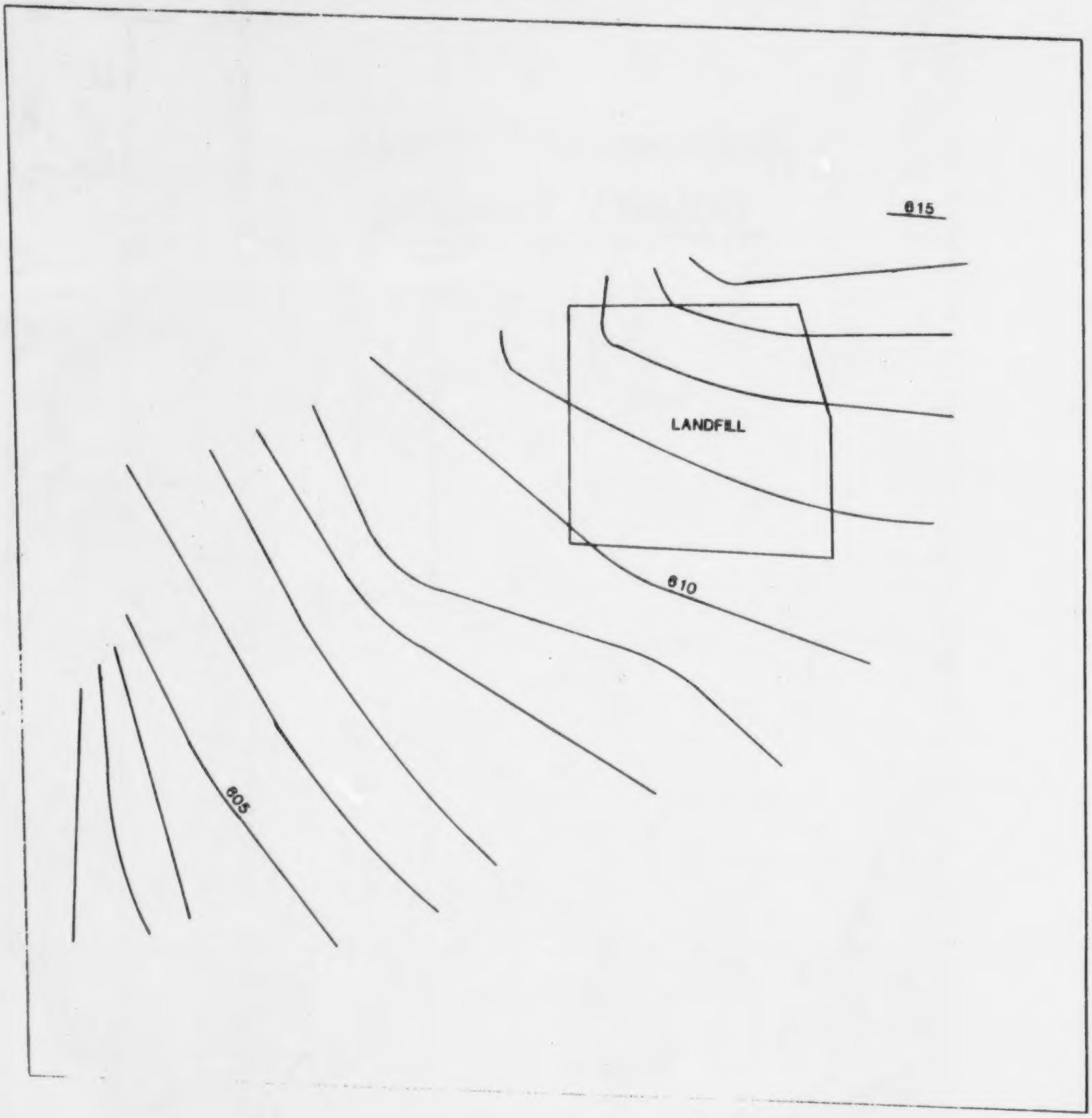
615
LANDFILL
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FIGURE 6-12 Revised piezometric contour map, based on vertically averaged observed heads.

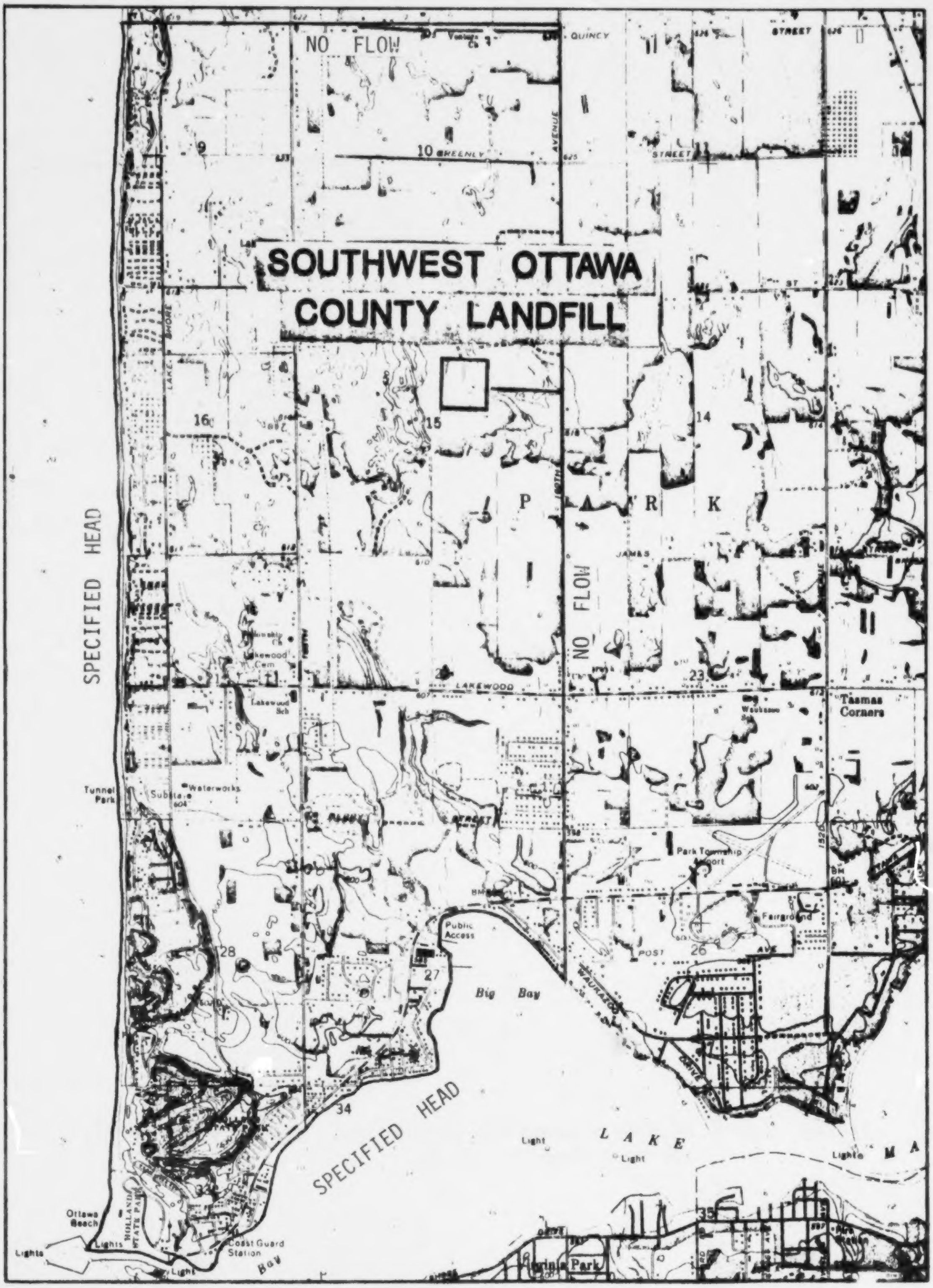
NO FLOW
SOUTHWEST OTTAWA
COUNTY LANDFILL
SPECIFIED HEAD
NO FLOW
SPECIFIED HEAD
QUINCY
STREET
GREENLY
STREET
AVENUE
LAKEWOOD
JAMES
P A R K
Lakewood Cem
Lakewood Sch
Tasmas Corners
Tunnel Park
Waterworks
Park Township Airport
Fairground
Public Access
Big Bay
POST
L A K E
M A
Light
Ottawa Beach
Coast Guard Station
Holland State Park
Lights
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FIGURE 6-13 Final boundaries used in regional model.

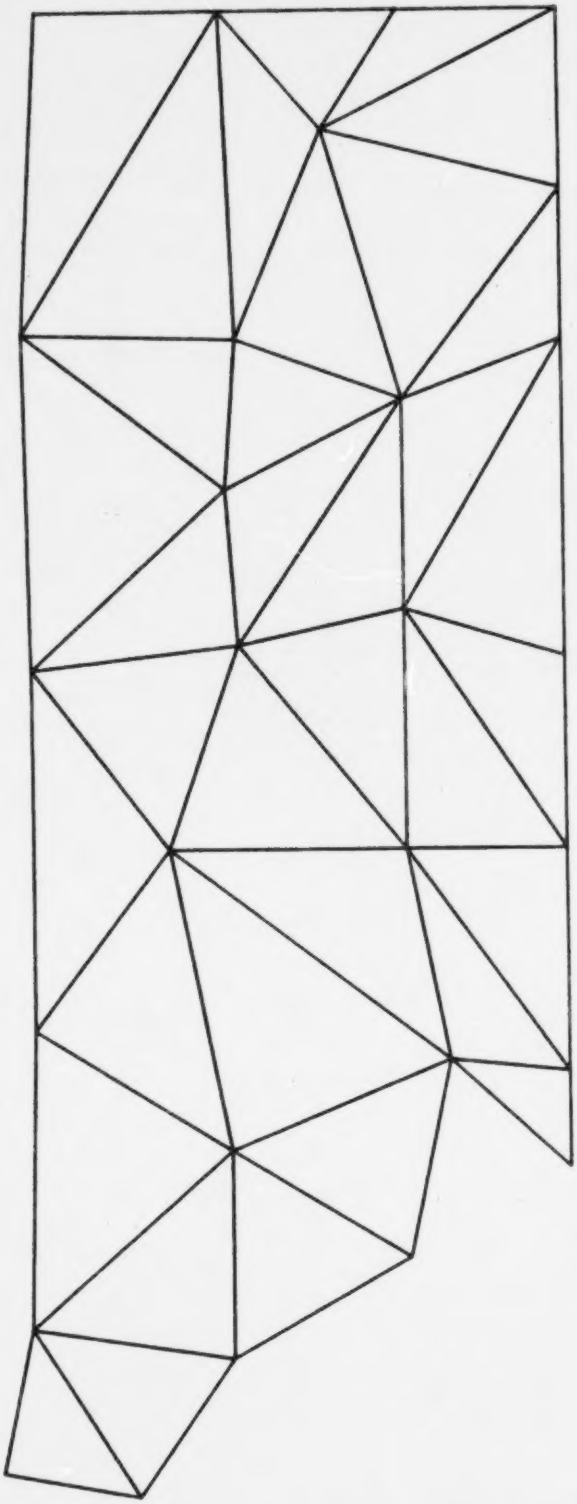


FIGURE 6-14 Final finite element grid for regional model.

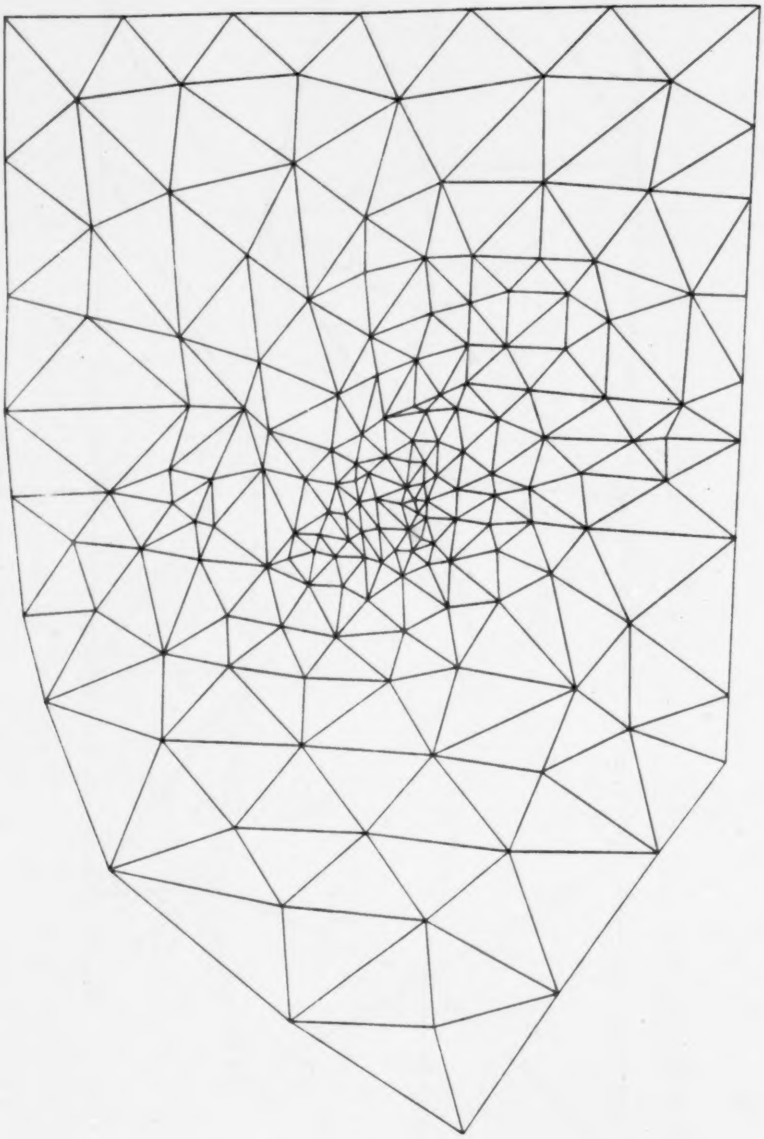


FIGURE 6-15 Final finite element grid for local model.

The computer model did yield a reasonable representation of the aquifer behavior as we currently understand it. Groundwater elevation contours generated by the model are very close to those developed from field observations (compare Figures 6-12 and 6-16). The effects of known and suspected lenses south and west of the landfill are represented. Figure 6-17 illustrates the impact of the lenses on the flow vectors. This clearly shows the preferential flow paths followed by most of the contaminants.

Model Application

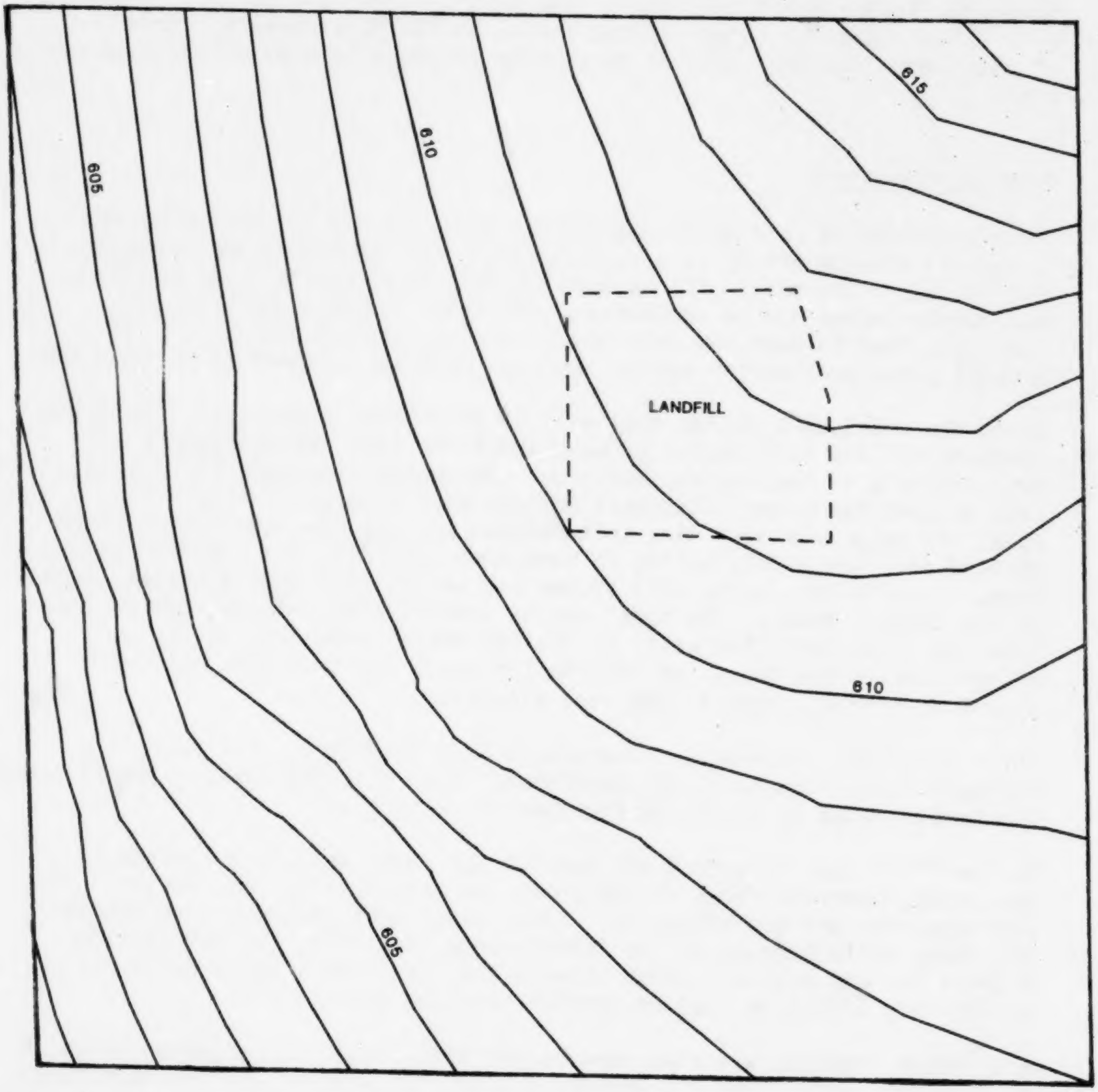
These complicated flow paths and the boundary effects of the lenses must be taken into account if an effective purge well system is to be designed. This is where the model will be most useful. Alternative pump locations and pumping rates can be evaluated. The model can help evaluate pump test data, and in turn new data can be used to improve the model. An optimal purge well system can be designed with the assistance of the model.

Using the model as a design tool will be an iterative process. The model contains all the information we have about the site and represents our best estimate of the aquifer behavior. As design proceeds, field tests such as pump tests and additional borings will have to be made. The model can help interpret this information, and the new data can be incorporated into the model, making it even more realistic and useful. Therefore, a preliminary purge well system can be designed with the assistance of the current model. The model can be updated with information developed from the first installed wells or aquifer tests. New information will either confirm the model, or provide the basis for improving the model, making it behave closer to the real situation.

Three alternate purge well systems have been evaluated. For each case a steady state flow field was developed. From this the system effectiveness can be evaluated by observing the zone of capture.

In the first case (Figure 6-18) two 100 gpm purge wells are located in the plume, near the edges of the known low permeability lens system. This configuration was not effective. Some contaminants would escape between the purge wells because of the interference created by the lens system. A third 100 gpm well was added between the first two (Figure 6-19), providing very effective capture through the lens system.

A different concept was simulated in the third case. A perimeter purge well system, with three 100 gpm wells along the western and southern landfill boundaries (Figure 6-20), was tried. This configuration would capture new leachate from the landfill, but a large portion of the existing plume would be unaffected.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LANDFILL
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FIGURE 6-16 Simulation piezometric contour map.

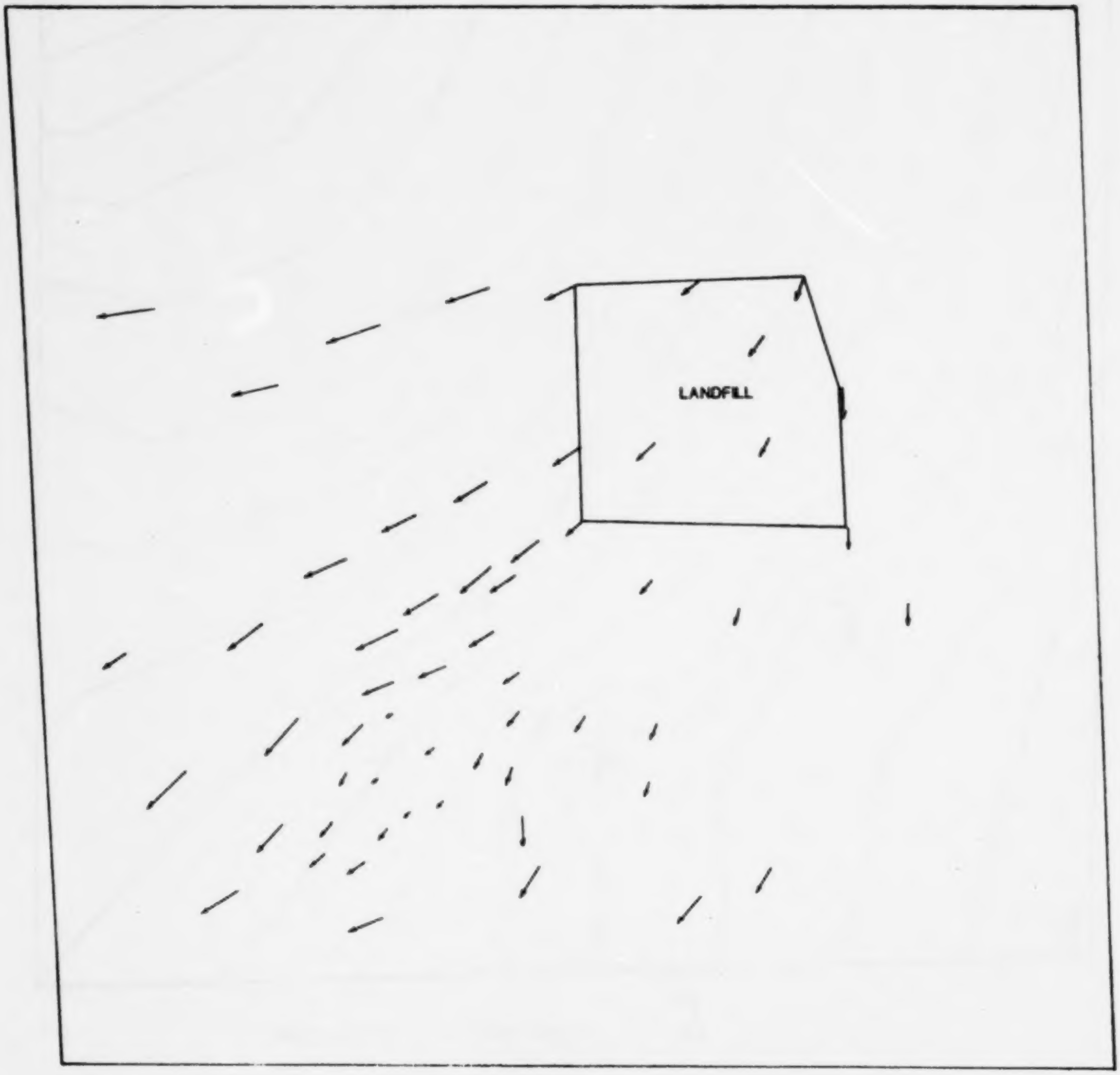
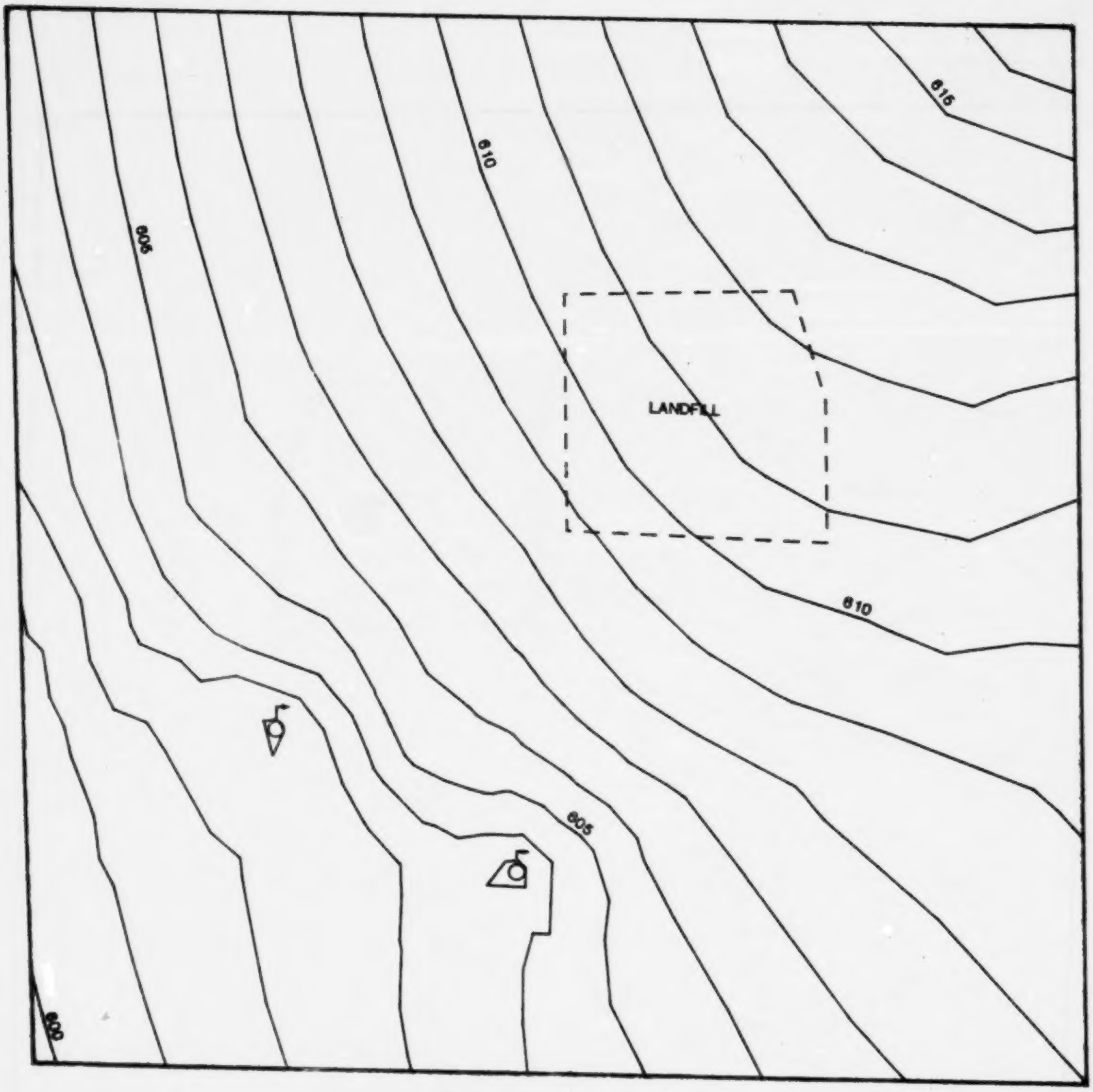


FIGURE 6-17 Example flow vector analysis. Arrows point in flow direction, length is proportional to volumetric flux per unit width at each point. Note that the silt lenses southwest of the landfill affect both flow direction and the amount of flow through the area.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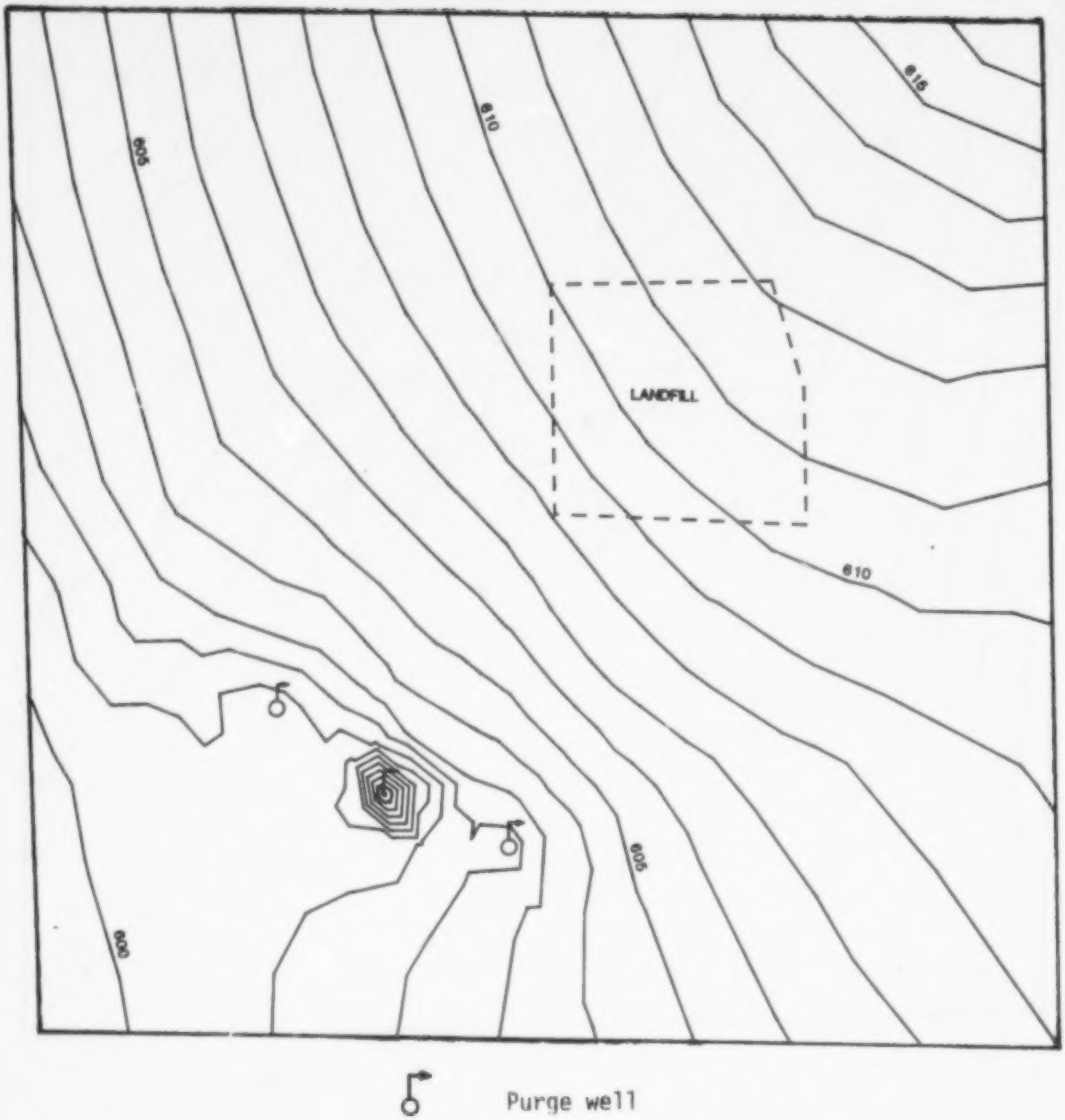
LANDFILL
610
605
600

Purge well @ 100 gpm

FIGURE 6-18 Two purge well system, steady state flowfield. Some contaminated water would pass between the purge wells through the lens system.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LANDFILL
610
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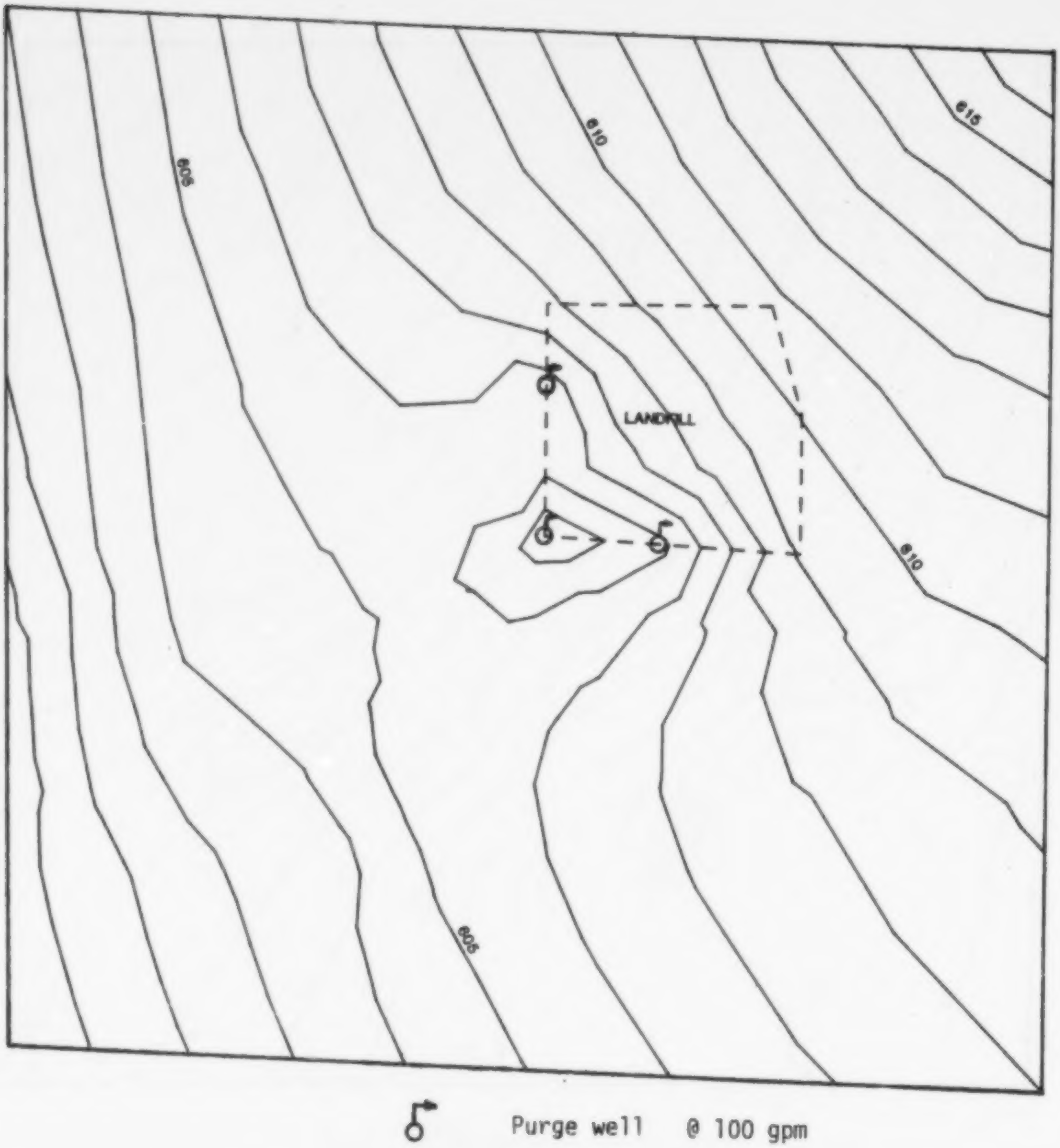
600
Purge well

FIGURE 6-19 Three purge well system, steady state flowfield. Note that it would not be necessary to pump the middle well at 100 gpm. All three wells are shown pumping at 100 gpm.


615
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LANDFILL
610
605
Purge well @ 100 gpm

FIGURE 6-20 Perimeter purge well system, steady state flowfield. This configuration would capture new leachate but most of the existing plume would escape.

Alternate systems can be simulated very quickly, easily and inexpensively once the model has been set up. Other configurations and pumping rates can be simulated. And if necessary an unsteady analysis can be made of a proposed system to see what happens to the flow field before steady state is reached. This would be very helpful for evaluating pump tests, but would probably not usually be necessary for evaluating overall purge well system effectiveness.

The model is ready for application. Further use is awaiting a decision to proceed with remedial action. The case study has demonstrated that complex groundwater systems (including some three-dimensional complexities) can be reasonably modeled. The model can be used to evaluate management alternatives.

CHAPTER 7

COMSTOCK TOWNSHIP

Comstock Township is located east of Kalamazoo. Forty-three residential wells in one subdivision (Figure 7-1) have been contaminated with chlorinated hydrocarbons. Detectable levels of trichloroethylene (up to 184 ppb) and Cis 1,2 dichloroethylene (up to 293 ppb) have been found in the wells. There is no known source for the contamination, and no recognizable patterns in the contaminated wells. Figure 7-2 illustrates the scatter of affected wells within the subdivision and range of concentrations of 1,1,1 trichloroethane. The contaminated wells are in a shallow aquifer, 25 to 30 feet deep. They are located in a relatively flat area adjacent to the Kalamazoo River. The known contaminated area is bounded by the Kalamazoo River to the south and a large sand and gravel hill to the north (see Figure 7-1). The extent of the contamination is not known and there is a potential for surface waters to be affected.

There are no ongoing discharges or waste handling activities that would appear to be responsible. Past waste dumping activities or material losses could be the cause. There are several suspected sources (see Figure 7-1), and it must be determined which site or combination of sites is responsible for the contamination. Field work was initiated to try to identify the source.

A reconnaissance model based on very limited data was made before field work began. It was the first attempt to estimate aquifer properties and boundaries and provided insight as to how the aquifer might behave. Field work was performed in stages. Each succeeding stage revealed an increasingly complex aquifer system. The model was reformulated and updated as new information became available. The model aided in understanding what might be happening in the aquifer system. It can test the reasonableness and consequences of hypotheses developed to explain aquifer behavior, and can help set criteria to be field checked. The model was kept simple so that it could be easily updated as field data became available. An analytical mass transport model was used to help determine whether a suspected source that was not directly up gradient could have caused the contamination.

Model Goal & Approach

The modeling goal was to incorporate modeling techniques with the field study and make effective use of computer simulation where appropriate. Data collection and modeling efforts were to be closely coordinated. By the time data collection was completed, we wanted to have sufficiently defined the scope of the problem and determined the hydrogeologic setting; and incorporated this information into a model capable of evaluating the management alternatives at the site.

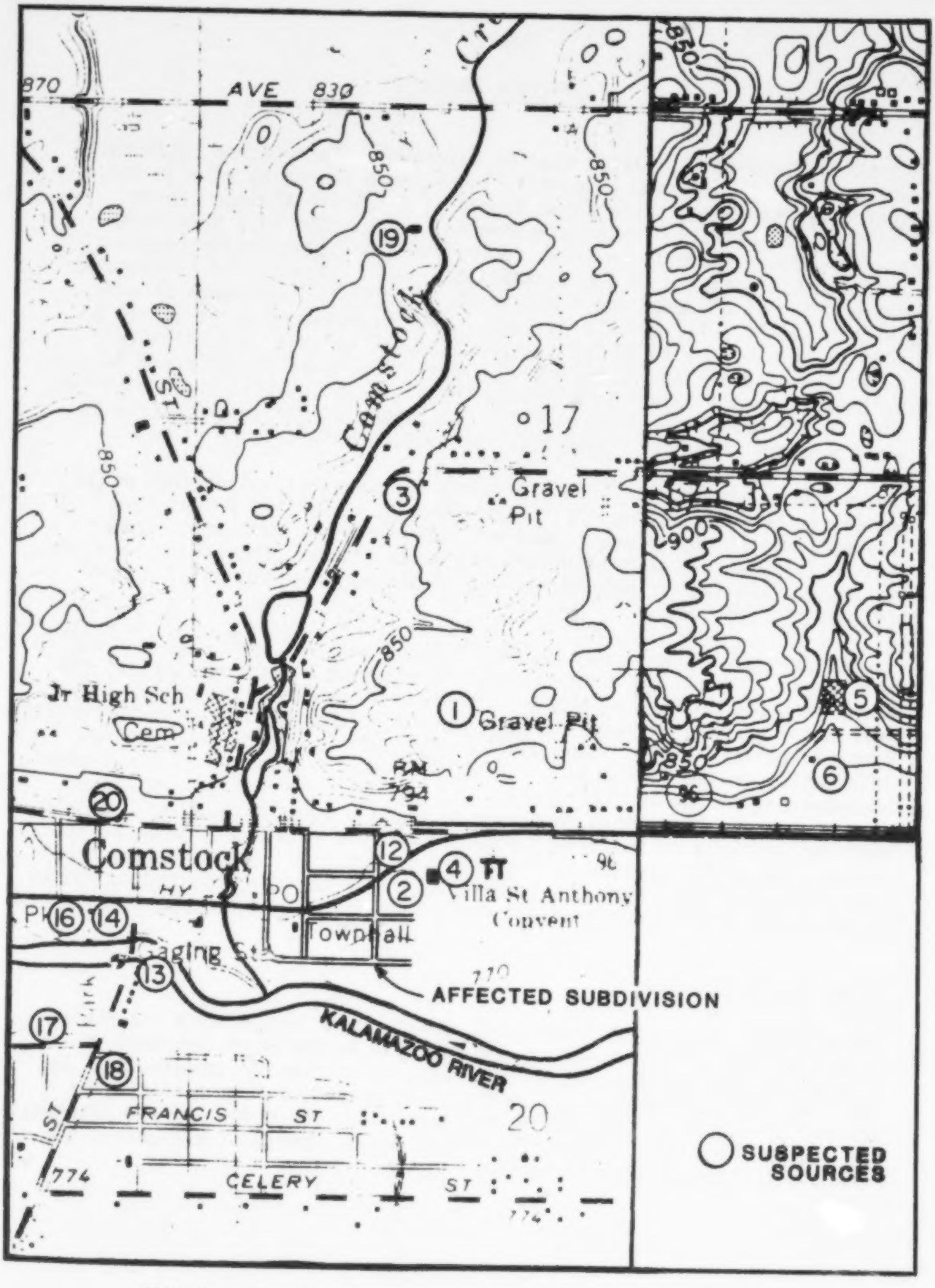
870
AVE 830
850
19
Comstock Cr
St
850
o 17
3
Gravel Pit
900
850
Jr High Sch
Cem
1 Gravel Pit
5
850
6
BM 794
20
Comstock
12
4
2
Villa St Anthony Convent
HY
PO
16
14
Townhall
Gaging Sta
13
AFFECTED SUBDIVISION
KALAMAZOO RIVER
17
Park St
18
FRANCIS ST
20
774
CELERY ST
774
SUSPECTED SOURCES

FIGURE 7-1 Comstock area; affected subdivision; and pricipal suspected sources.

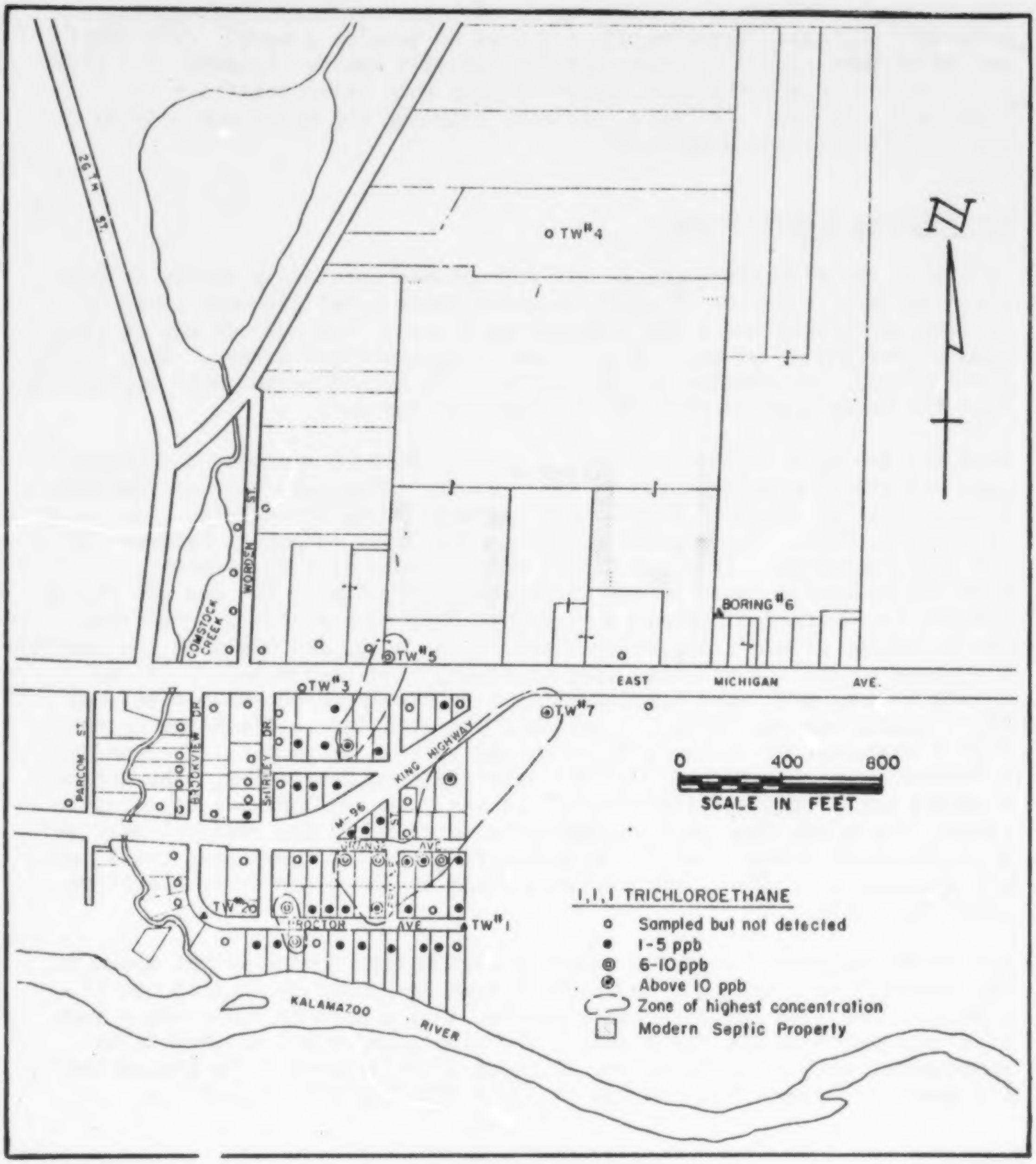
M-96 ST.
COMSTOCK CREEK
WORDEN ST.
TW#4
TW#5
TW#3
TW#7
BORING#6
EAST MICHIGAN AVE.
PARCOM ST
BROOKVIEW DR
SHIRLEY DR
KING HIGHWAY
M-96
AVE
TW#2
PROCTOR AVE
TW#1
KALAMAZOO RIVER
N
0 400 800
SCALE IN FEET
1,1,1 TRICHLOROETHANE
○ Sampled but not detected
● 1-5 ppb
◎ 6-10 ppb
⊙ Above 10 ppb
Zone of highest concentration
☐ Modern Septic Property

FIGURE 7-2 Distribution of 1,1,1 Trichloroethane in subdivision wells.

The approach used was straightforward. All the available hydrogeologic data were gathered, interpreted, and used to develop a model. The model was to be used to aid in understanding possible aquifer behavior and test the feasibility and implications of various data interpretations or working hypotheses. As field data were gathered the model was updated and used to test new hypotheses.

Hydrogeology & Model Input

Initially the site hydrogeology was not defined adequately enough to make modeling very reliable. A crude reconnaissance model was made based on surface topography and a few domestic well logs. The purpose was to gain some understanding of how the groundwater system might behave. Very little hydrogeologic information was available. The author worked with geologists from the Water Quality Division to interpret the data.

From the few well logs in the area a general picture emerged of a phreatic sand and gravel aquifer north of the Kalamazoo River and east of Comstock Creek. West of Comstock Creek there appeared to be a confining clay layer near the surface. The aquifer bottom seemed to be somewhere between 700' and 750' elevation. Sand and gravel would likely be very permeable, with the hydraulic conductivity estimated to be between 140 and 280 ft/day. Surface topography was examined to try to determine boundary conditions. The Kalamazoo River is the major river in the area, and would be the aquifer discharge point. It was then used as a specified head boundary of 760'. Comstock Creek and Lower Comstock Lake were likely to be boundaries, but their nature was not known. They could act as either a discharge or recharge boundary, or possibly both, or not even be hydraulically connected. A sensitivity analysis would investigate these possibilities. The northern boundary would be prescribed heads. It was drawn following a topographic ridge. The elevations were estimated by determining the regional gradient along Comstock Creek from the Kalamazoo River to the swamp near Lyons Lake, and assuming a gradient from Comstock Creek to the water table elevation under the ridge.

The estimated water table elevations were consistent with values shown in the generalized hydrologic map of this area developed by Deutsch, et al (1960). A no flow boundary was estimated to the east by following a surface depression to the Kalamazoo River. The aquifer was assumed to be homogeneous with a recharge rate of about 8 inches/year. The boundaries are shown in Figure 7-3, and the finite element grid in Figure 7-4.

Model Results and Update with Field Data

Various sensitivity analyses were run. The most interesting results occurred when Lower Comstock Lake was modeled as a specified head boundary at normal pool elevation of 790', and specified heads were set along Comstock Creek according to the surface topography. The lake recharged the aquifer, with

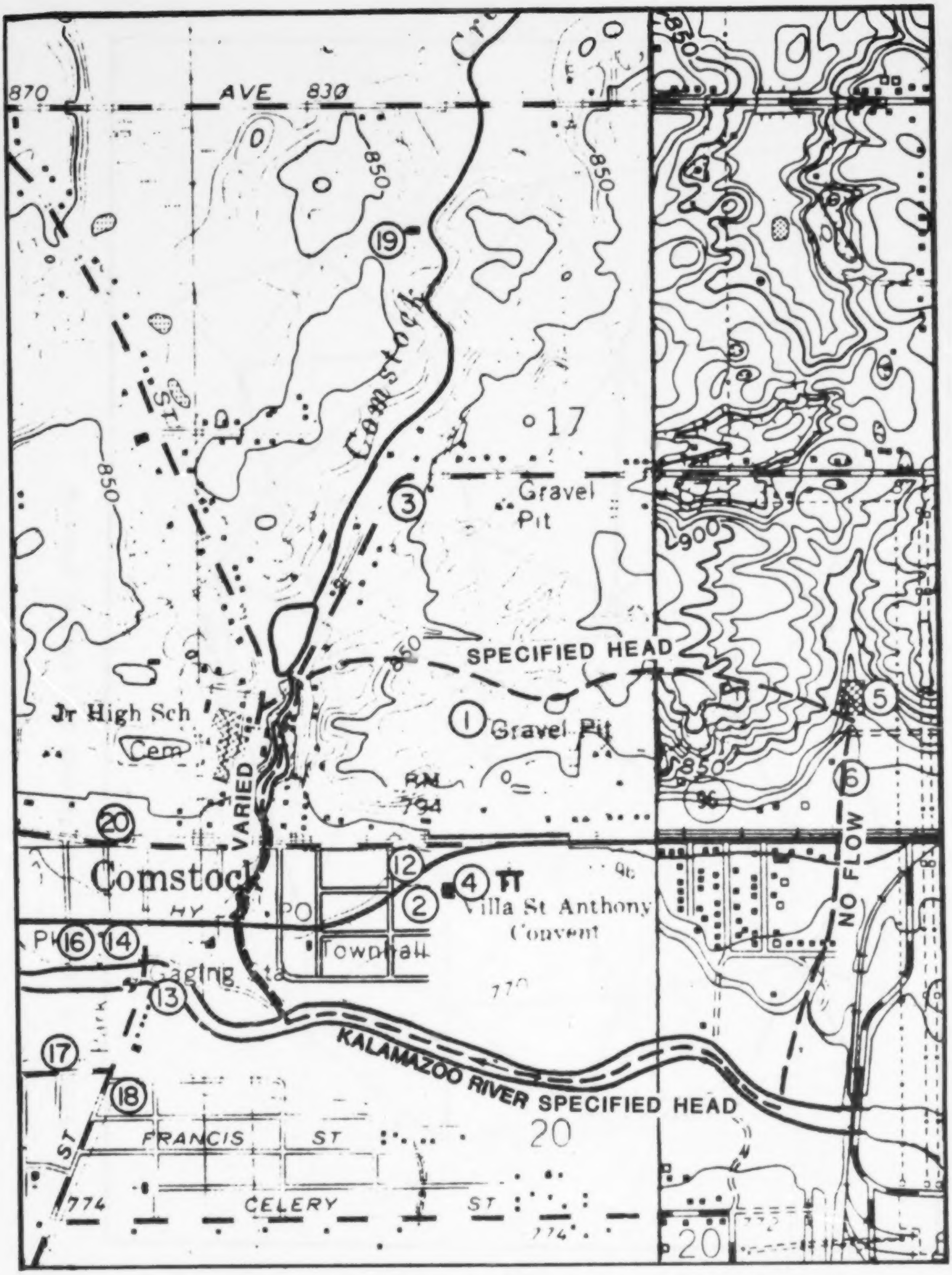
870
AVE 830
850
850
850
19
Comstock Cr
17
3
Gravel Pit
900
850
SPECIFIED HEAD
1
Gravel Pit
5
6
Jr High Sch
Cem
VARIED
BM 794
96
20
NO FLOW
12
4
2
Comstock
HY
PO
Villa St Anthony Convent
16
14
Townhall
Gaging Sta
13
770
17
18
KALAMAZOO RIVER SPECIFIED HEAD
20
FRANCIS ST
CELERY ST
774
774
20
ST

FIGURE 7-3 Boundary conditions used in first model. The boundary along Comstock Creek was varied; specified head, no flow, and leakage boundaries were all used.

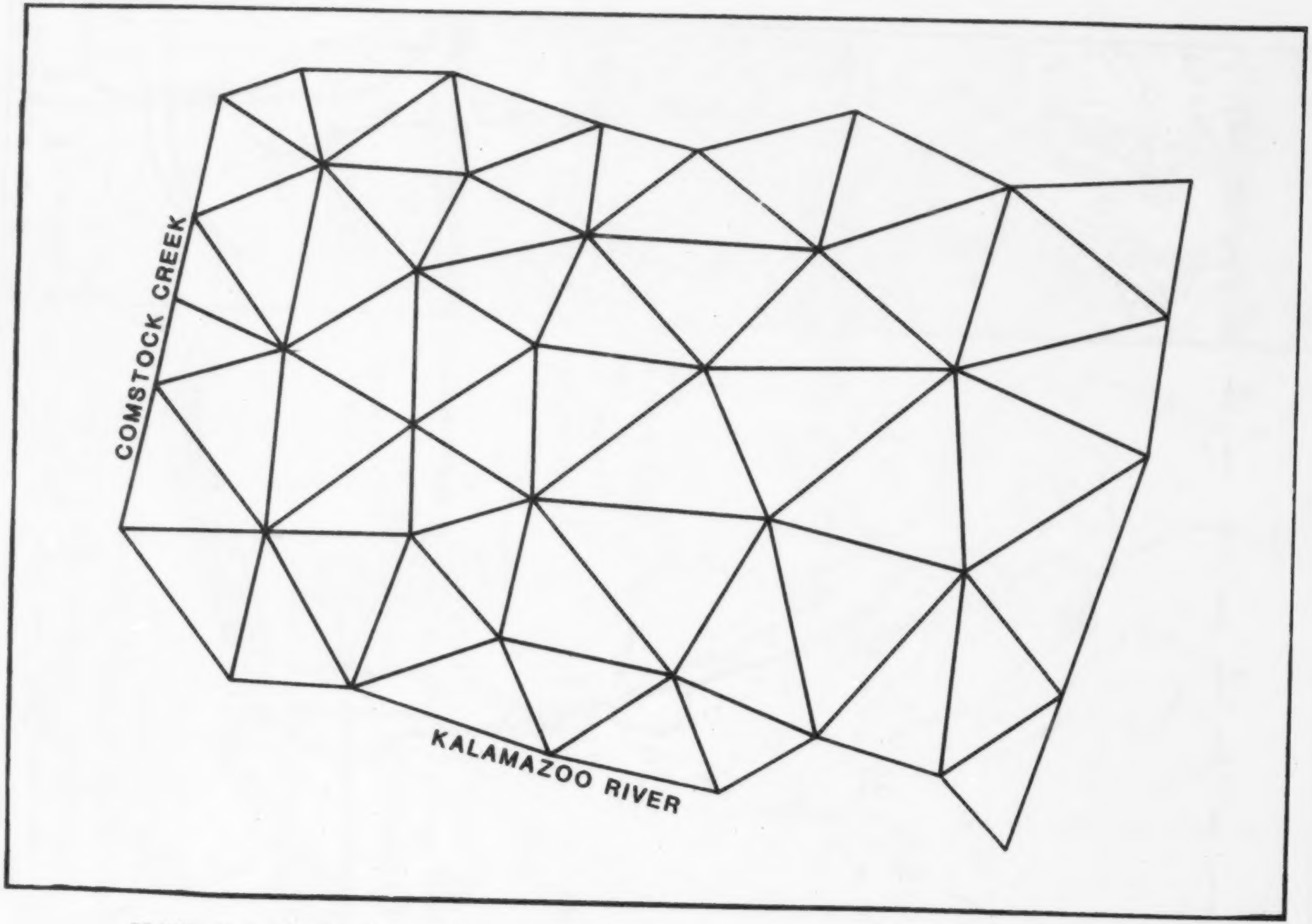
COMSTOCK CREEK
KALAMAZOO RIVER

FIGURE 7-4 First finite element grid used at Comstock.

a gradient to the southeast, that turned back to the southwest, discharging into Comstock Creek (see Figure 7-5). This provided a possible physical explanation for the data which showed contamination east of Brookview Road but not between the road and Comstock Creek; i.e., the local flow field may be acting as a barrier to contaminant movement. The total aquifer discharge was consistent with estimated base flow pick up in the Kalamazoo River. This model was consistent with all the known data, but the data were very meager and more qualitative than quantitative.

A field investigation was initiated and field data quickly showed that the first crude model was not at all realistic. The gradient was in error, and field data did not match the model results (Figure 7-6). The model was reformulated using the field data. The field data have not yet resulted in a clear, consistent interpretation of the site hydrogeology. So the model is being used to test various hypotheses or interpretations of the hydrogeology, to help determine which are feasible and help determine what the most appropriate next step is in the field work.

Data interpretation was coordinated with geologists from Environmental Data, Inc., the firm contracted to perform the hydrogeologic study, and geologists from Water Quality Division. TW #6 did not produce water, apparently the aquifer pinched out in that vicinity. So the eastern no flow boundary was moved to this area, opening eastward in the floodplain area (Figure 7-7). The hydrogeology is not yet understood in the vicinity of TW #3 and TW #5. The aquifer may be pinched out in that area or there may be a lense system. Two alternative boundaries were then chosen. One continued to use Comstock Creek as the western boundary; the other had a no flow boundary through the vicinity of TW #3 and TW #5, opening westward in the floodplain area. A prescribed head boundary was set based on TW #4 to the north. And the Kalamazoo River was maintained as the prescribed head discharge boundary. The finite element grid was designed to accommodate either interpretation of the western boundary (Figure 7-8). The estimated aquifer bottom elevations were interpolated from the field data (Figure 7-9).

Output from the second model compared well with field values of piezometric head (Figure 7-10). This match required the assumption that the hydraulic conductivity of the aquifer along the hillside is only 25% of that near the Kalamazoo River. The great head loss between TW #4 and TW #7 suggested that the hydraulic conductivity along the hillside is much less than in the aquifer along the floodplain. Several sets of hydraulic conductivity were tried. Values that resulted in a reasonable fit between simulation and field values were: K (upland) = 70 ft/day and K (floodplain) = 280 ft/day. The results compared in Figure 7-10 are from a simulation using the western no flow boundary. The simulated heads are still a little high, but the contour patterns look good. Flow to the river may be overestimated, and the velocities are high; but on the whole the simulation appears to be satisfactory. It may be possible to improve the simulation by reducing the hydraulic conductivities while maintaining their relative ratios. This was not done at this stage because the simulations were only exploratory

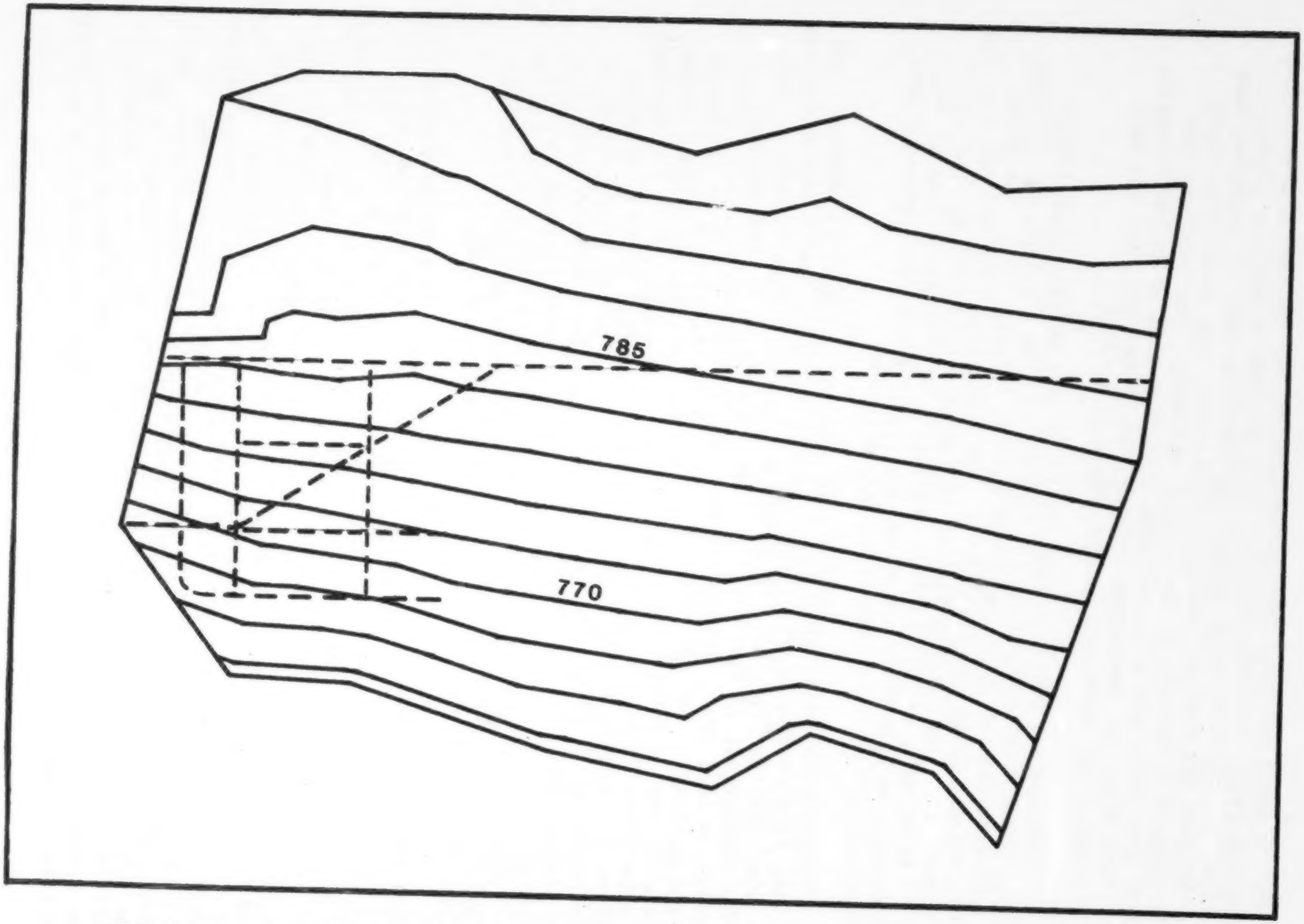

FIGURE 7-5 Simulation results from first model. The contour interval is 3 feet.

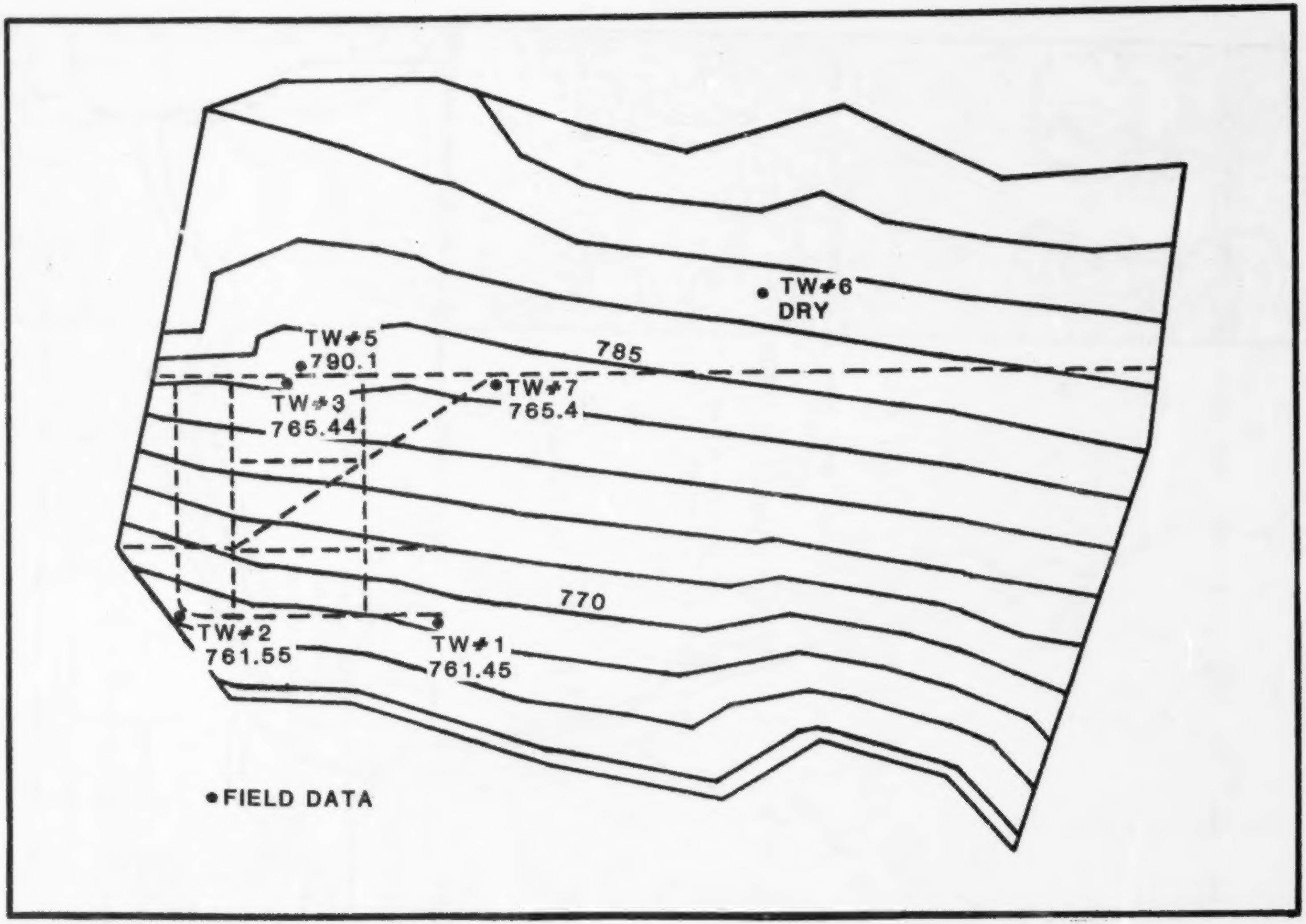
TW#6
DRY
785
TW#5
790.1
TW#3
765.44
TW#7
765.4
770
TW#2
761.55
TW#1
761.45
•FIELD DATA

FIGURE 7-6 Field data compared with first model results. The contour interval is 3 feet.

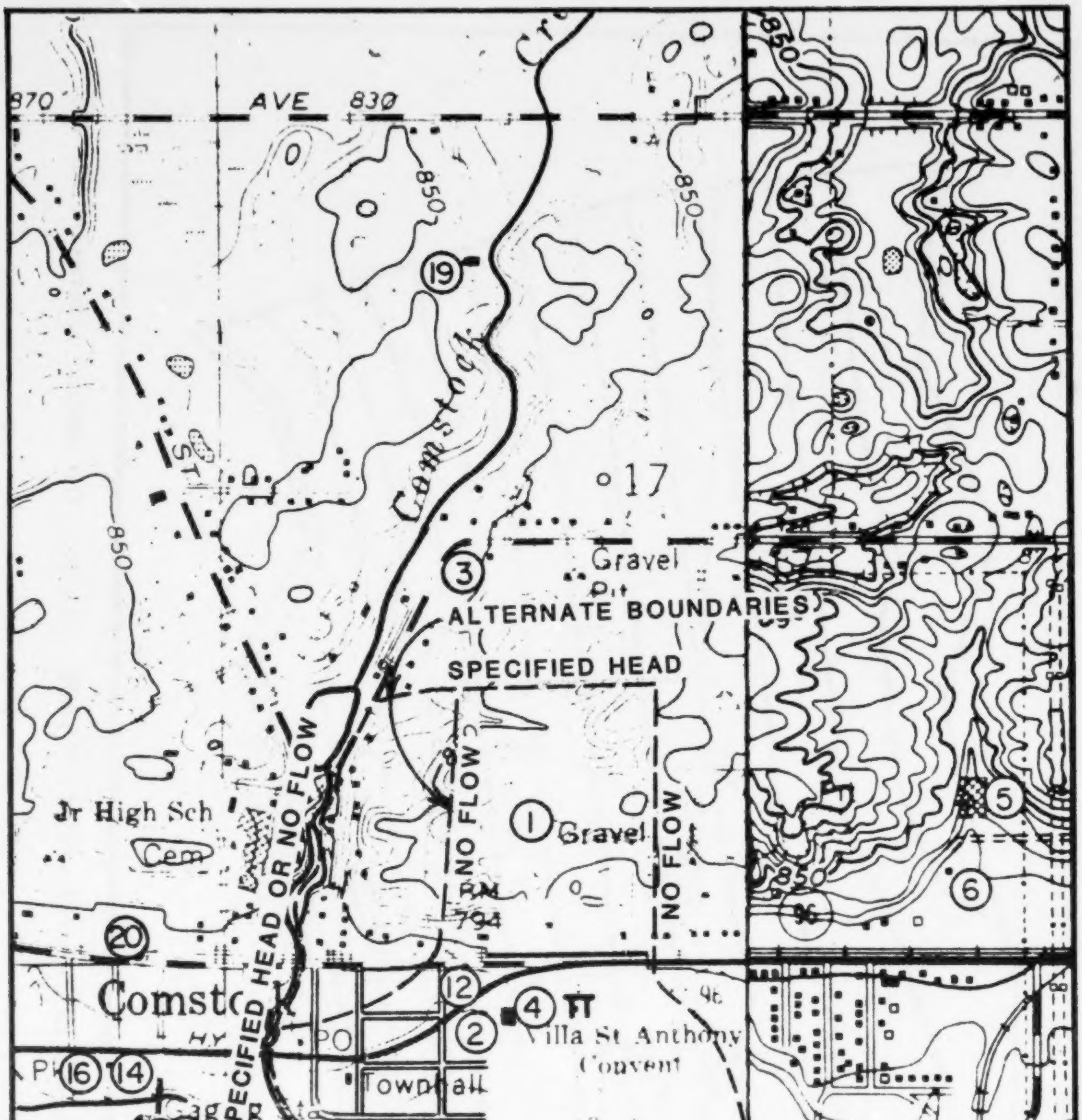
870
AVE 830
850
850
850
19
Comstock
17
3
Gravel Pit
ALTERNATE BOUNDARIES
SPECIFIED HEAD
SPECIFIED HEAD OR NO FLOW
NO FLOW
NO FLOW
1 Gravel
BM 794
5
6
850
96
Jr High Sch
Cem
20
Comstock
12
4
2
Villa St Anthony Convent
PO
Townhall
16
14
13
SPECIFIED HEAD
KALAMAZOO RIVER
17
18
FRANCIS ST
20
CELERY ST
774
774
20
ST
ST

FIGURE 7-7 Boundary conditions used in second model.

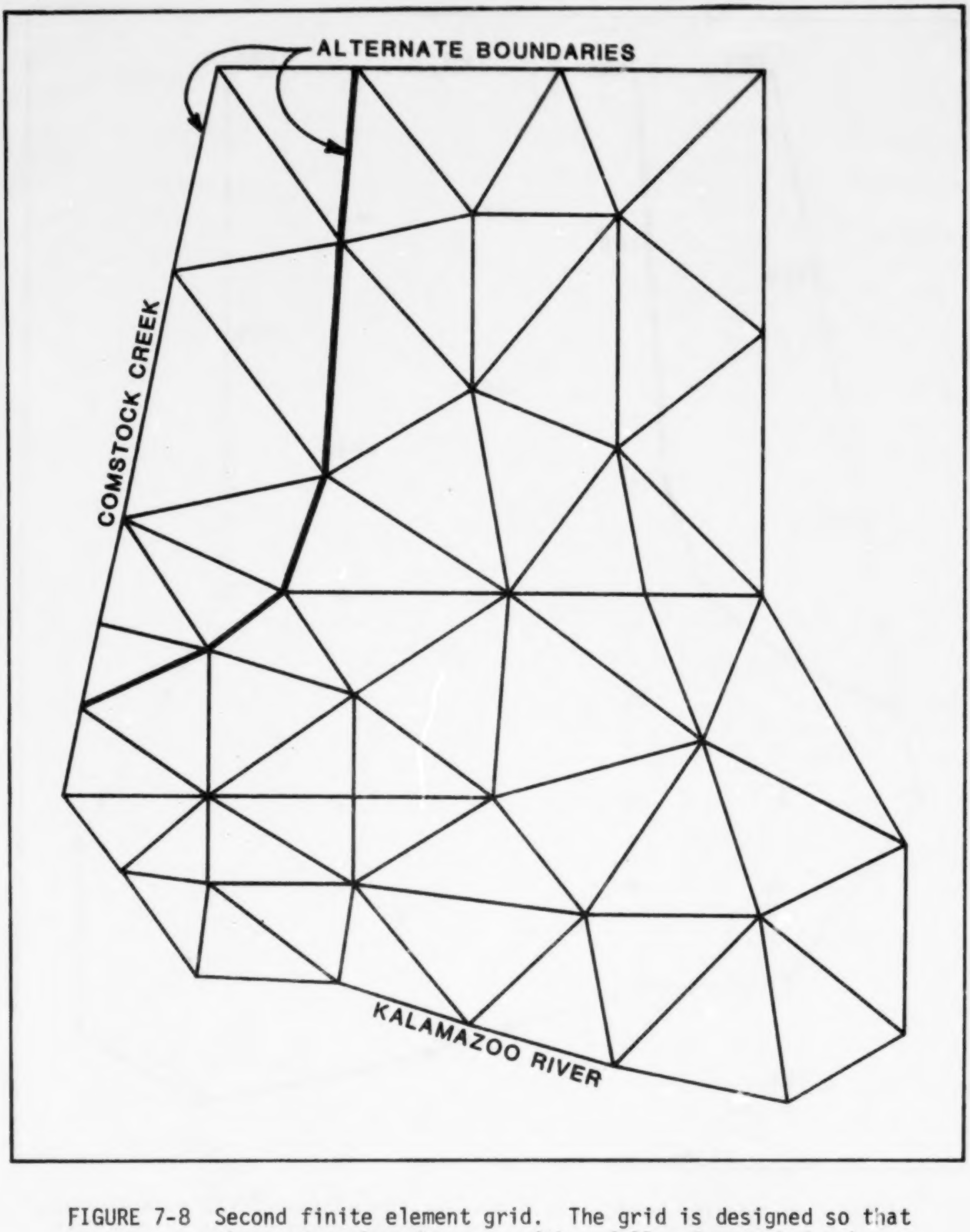
ALTERNATE BOUNDARIES
COMSTOCK CREEK
KALAMAZOO RIVER

FIGURE 7-8 Second finite element grid. The grid is designed so that the western boundary can either follow Comstock Creek or a possible no flow boundary further east.

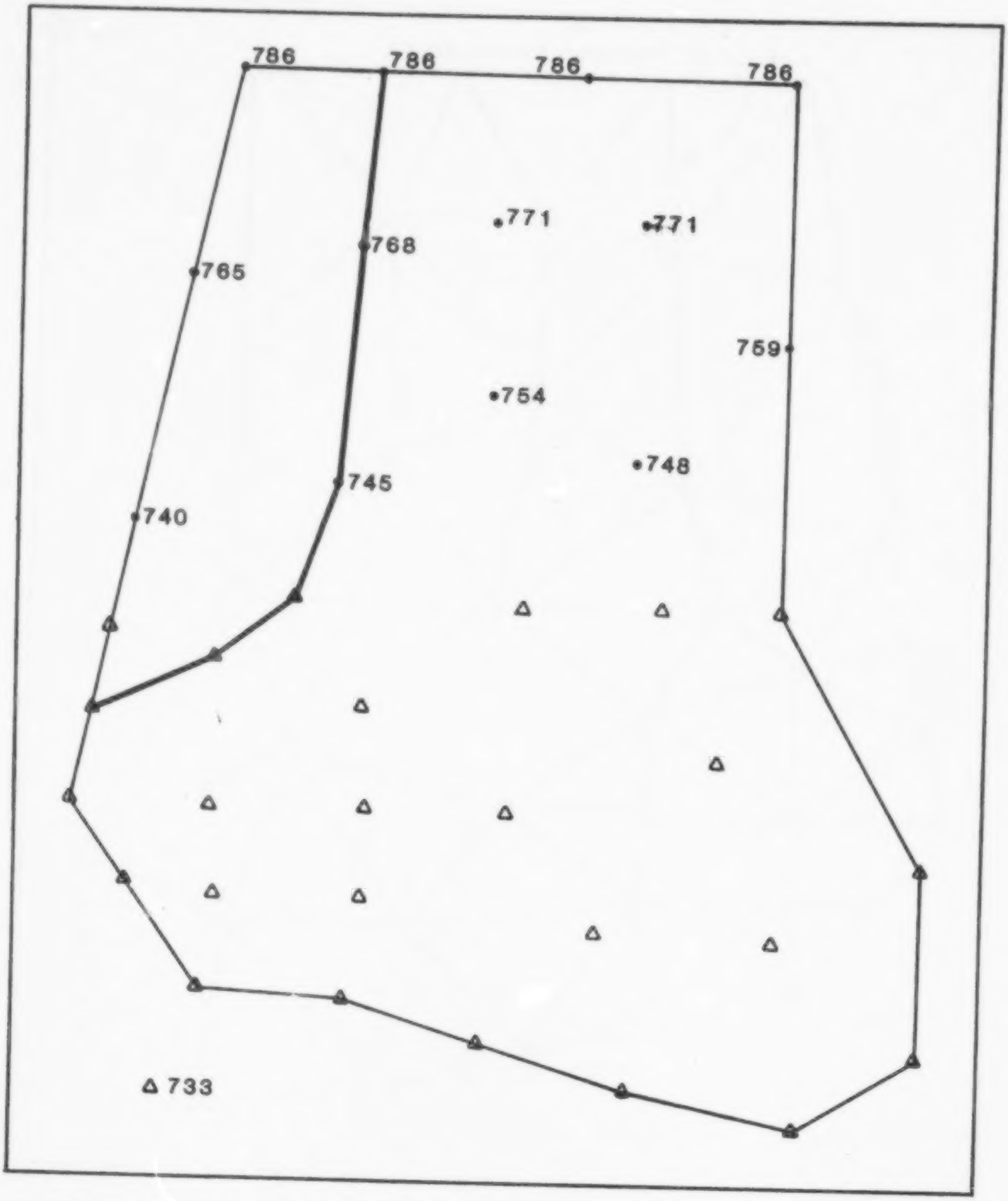
786
786
786
786
771
771
768
765
759
754
748
745
740
Δ 733

FIGURE 7-9 Aquifer bottom elevations estimated from field data and used in model. The bottom elevation was set at 733 in the flat area near the Kalamazoo River.

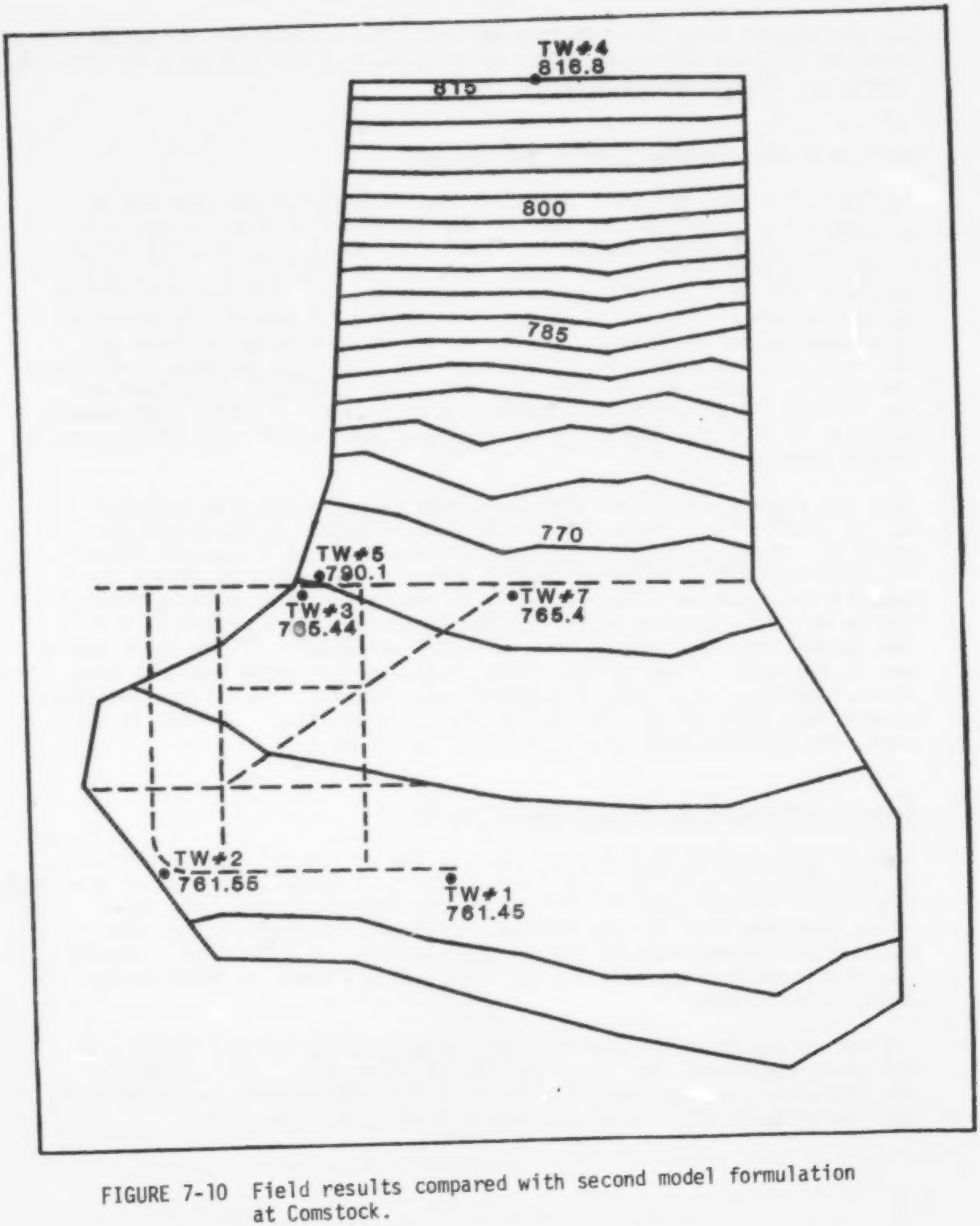
TW#4
816.8
815
800
785
770
TW#5
790.1
TW#3
765.44
TW#7
765.4
TW#2
761.55
TW#1
761.45

FIGURE 7-10 Field results compared with second model formulation at Comstock.

and did not yet have to be greatly refined. The assumptions and parameters used can be field verified. Other factors, such as the influence of Comstock Creek, can also be tested with the model.

Analytical Mass Transport Model Application

An analytical mass transport model was used to evaluate the possibility of dispersion accounting for some of the contamination found in the subdivision. One possible source (location 1 in Figure 7-1) does not appear to have a streamline from the source area to the subdivision. This does not mean that it is eliminated as a possible source. The possible effects of lateral dispersion must still be investigated. A sensitivity analysis of dispersion was performed. The source was assumed to be constant and 500 feet wide. Since an analytical model was used, the boundary condiitions and aquifer properties are very idealized. The flowfield is uniform and the aquifer is homogeneous and infinitely extensive. A rather high seepage velocity of 6 ft/day from the flow model was used, and a range of dispersion coefficients was tried.

When the plume had traveled 1800 feet downstream, it would be adjacent to the subdivision. At this point the lateral extent of the plume was examined. Small dispersivities, in the range found at Production Plated Plastics (up to 5'), would not have sufficient dispersion to affect the subdivision. However, dispersivities in the range found at Story Chemical (up to 60', see Appendix 2) could affect the subdivision, especially if the lateral and longitudinal dispersivities are equal. If the dispersivity was in the order of 10% of the travel distance, then there would be even more dispersion. The results indicate that location 1 is still a possible source, and parts of the analysis can be field verified. If this is the case, the concentrations should increase to the east.

Model Coordination with Field Investigation

Through this type of sensitivity analysis the utility of the field data is extended, and a better understanding of the groundwater system is developed. The results of the model at this stage were not conclusive. The model is an effective tool for exploring possible data interpretations, and testing the consequences of these interpretations or hypotheses. However, the model results must be field verified, since a model is never better than its data base.

Laboratory results indicated that the concentrations did not increase to the east; therefore, the source was not at location 1. The lab results did indicate that the likely source is on the same property as location 1, but nearer to TW #5. Field work next concentrated in this area.

This case study demonstrates that it is possible to closely coordinate computer modeling with the field data collection. The model allows new interpretations to be rapidly incorporated to conform with new field data and an increasing complex data pool. Current theories and physical interpretations can be analyzed and a better understanding of the aquifer is developed.

CHAPTER 8

PRODUCTION PLATED PLASTICS

Production Plated Plastics (PPP) is a small facility that metal plates plastic automotive components. It is located in Richland, about 9 miles northeast of Kalamazoo (Figure 8-1). DNR investigations have repeatedly found significant concentrations of dissolved chromium and nickel in the seepage lagoons that receive the plant's wastewater discharge. The company's own monthly operating reports have shown effluent chromium concentrations of over 14 ppm in 1977. Evidence of spills has also been found with puddles on the site containing 1200 ppm chromium. Several nearby residential wells have been contaminated with chromium, some with concentrations over 10 ppm. The EPA primary drinking water standard is 0.05 ppm. Water quality information gathered around the site indicates that there may be a relatively "low grade" constant contaminant source, such as the seepage lagoons, and at least one "slug" of contamination has affected nearby wells, possibly originating from spills on the site or temporary changes in the source conditions of the lagoons.

DNR has been in litigation with the firm since 1977. Some of the affected wells have been replaced by PPP, and a hydrogeologic investigation of the site was started and several monitoring wells installed. PPP agreed to complete the hydrogeologic investigation by defining the extent of the contamination, but no further work was done until May 1982. DNR wants the investigation completed and remedial clean up measures taken.

The available information is quite different than the previous two case studies. Local health department personnel monitored chromium concentrations in some of the affected domestic wells for over a year. This gave a time history of the contamination and some detailed information about the slug that passed through the groundwater system. The hydrogeologic study that was started gave detailed information about the local geology and piezometric heads. Figure 8-2 shows the location of monitored domestic wells and specially installed monitoring wells. The aquifer near the site is trough shaped, probably a buried channel. The maximum depth is about 70 feet and it pinches out to the northeast, and the saturated thickness decreases markedly to the southwest (see Figure 8-3). It is a permeable sand and gravel aquifer.

A flow model was used to help interpret the field data and reasonably simulate the groundwater flow field. Flow model results were used as input to the mass transport models. The mass transport models were used to predict where the plume might currently be located and what concentrations might be expected. Model results helped direct where new monitoring wells should go. The flow model was closely coordinated with the new field work. It helped interpret the new field data, which indicated the presence of a highly permeable "channel" and very low permeability zones. These complexities were successfully incorporated into the model. It was then used to simulate pump tests and evaluate proposed purge well system designs.

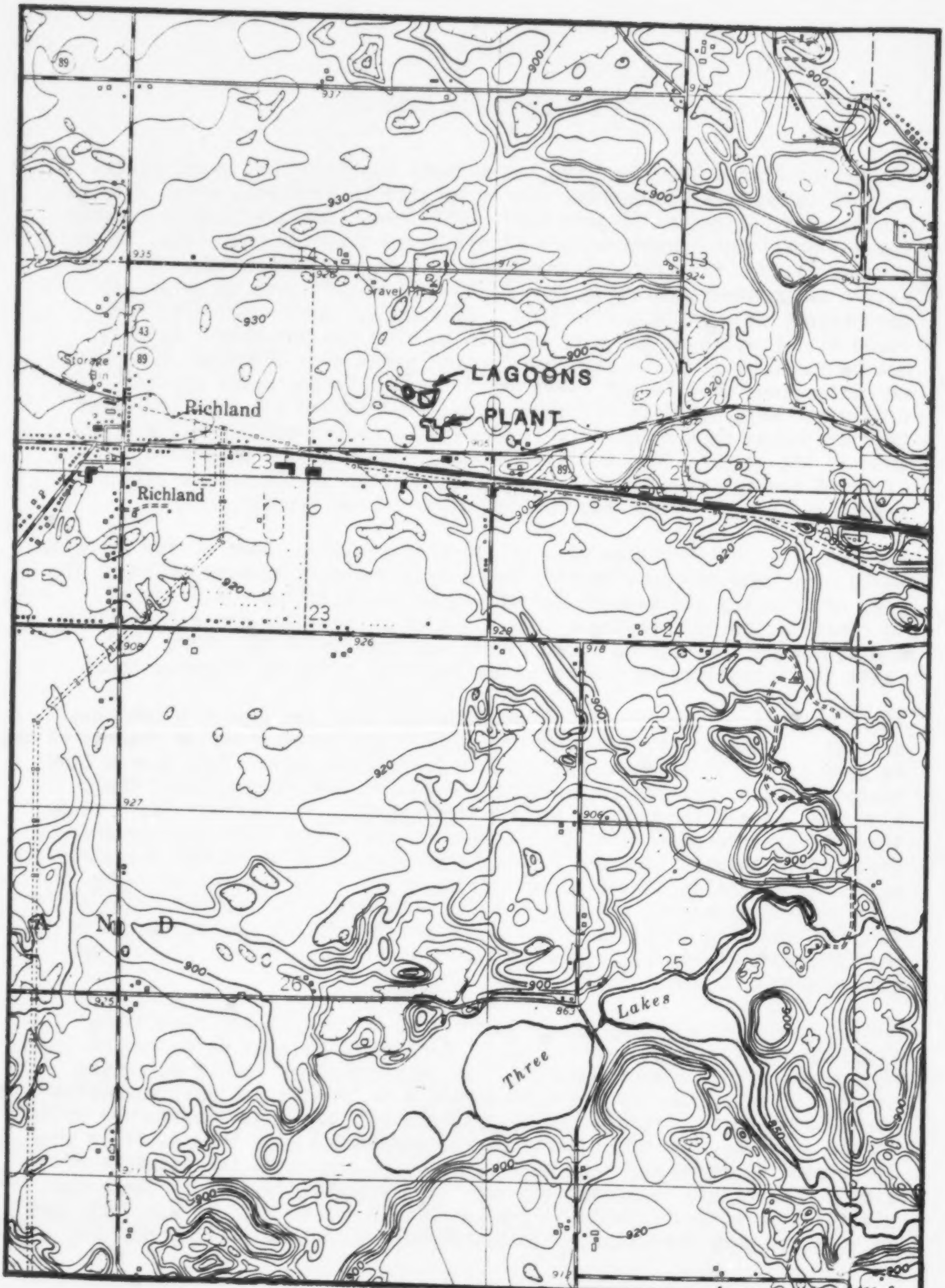
LAGOONS
PLANT
Richland
Richland
Storage Bin
Gravel Pit
Three
Lakes
A
N
D
14
13
23
23
24
25
26
89
43
89
89
900
920
930
930
937
935
926
926
929
918
906
927
908
915
863
912

FIGURE 8-1 Richland area and Production Plated Plastics.

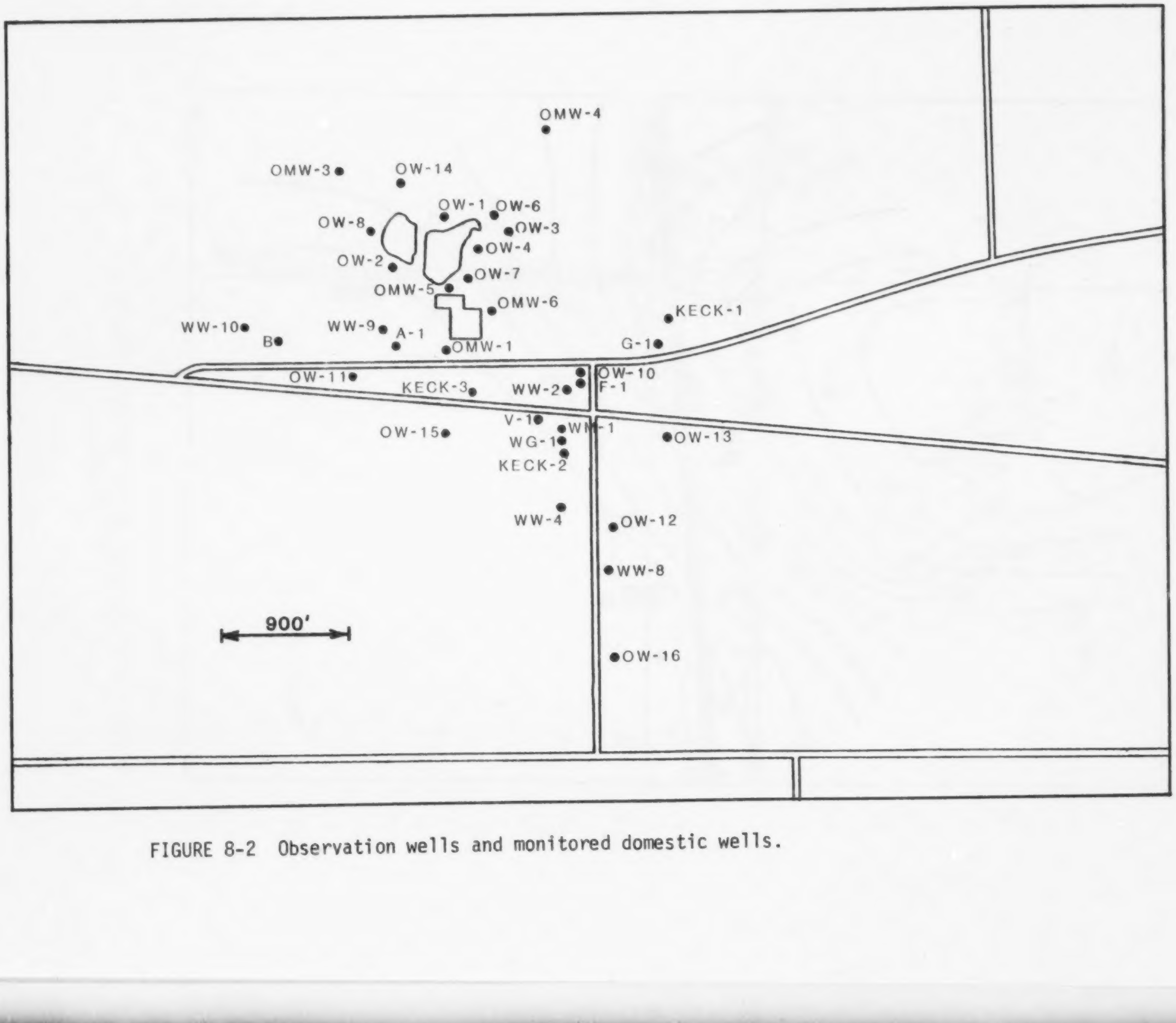
OMW-4
OMW-3
OW-14
OW-1
OW-6
OW-3
OW-8
OW-4
OW-2
OW-7
OMW-5
OMW-6
KECK-1
WW-10
WW-9
A-1
B
OMW-1
G-1
OW-10
OW-11
KECK-3
WW-2
F-1
V-1
WM-1
OW-13
OW-15
WG-1
KECK-2
WW-4
OW-12
WW-8
900'
OW-16

FIGURE 8-2 Observation wells and monitored domestic wells.

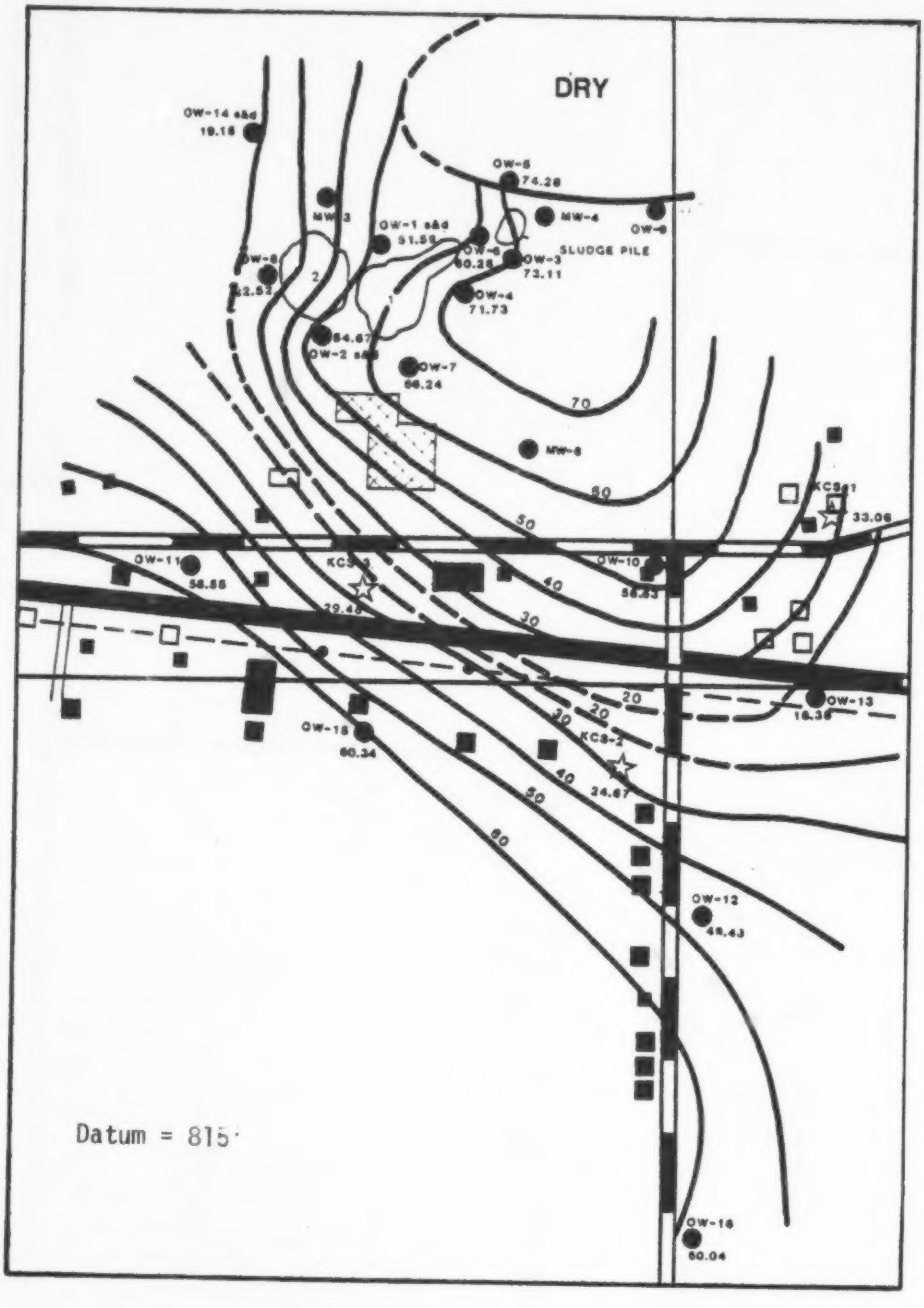
DRY
OW-14 s&d
19.16
MW-3
OW-1 s&d
51.58
OW-5
74.28
MW-4
OW-9
SLUDGE PILE
OW-8
52.52
2
1
OW-6
60.28
OW-3
73.11
OW-4
71.73
54.67
OW-2 s&d
OW-7
66.24
70
MW-5
60
50
KCS-1
33.06
OW-11
58.55
KCS-3
29.48
OW-10
56.33
40
30
20
20
30
OW-13
18.38
OW-15
60.34
KCS-2
24.67
40
50
60
OW-12
48.43
Datum = 815'
OW-16
60.04

FIGURE 8-3 Aquifer bottom contours determined from field investigation.

Model Goal & Approach

The goal of the modeling effort was to analyze the flow field, taking into account the known geometry and boundary conditions of the aquifer. We also wanted to make an effort to predict the fate of the contaminants if no remedial actions are taken, and to assess possible remedial solutions. Since the hydrogeologic investigation was not completed, there was no information about the contamination front. *The modeling objective was to predict where the plume might be, and help direct any future hydrogeological investigation.* Additional field work began in May 1982, after the modeling was completed. The completed model was used to help direct the work, and was updated with the new data.

The modeling approach was divided into two major components, the flow model and the mass transport model. AQUIFEM was used for 2-D flow simulation. It is capable of incorporating the aquifer geometry and boundary conditions estimated for the system. Once the flow model is properly calibrated against known piezometric heads and groundwater seepage velocities, its output can be used as input to the mass transport models. Because of the uncertainty in mass transport modeling, and to evaluate the effectiveness of different approaches, three different mass transport models were used. They included analytical models, the USGS Method of Characteristics model, and a finite element model - GEOFLOW. Each has its own set of strengths and weaknesses. Analytical models are very quick and easy to use but the boundary conditions are very idealized. The Method of Characteristics is stable and accurate for advection dominated situations, though the USGS code has many limitations. And finite elements can readily conform to complex geometries, although numerical dispersion can be a problem in advection dominated situations.

Hydrogeology & Model Input

A good flow model is the cornerstone of a hydrogeological evaluation, particularly if mass transport is also to be modeled. The geologic data have to be interpreted and schematized for the model. Available data consist of monitoring wells put in during hydrogeologic field work (Figure 8-2) and several domestic well logs in the area (Figure 8-4). Domestic well logs are not highly reliable sources of information. Their elevations are not surveyed in, recorded depths are approximate, and description of the lithology is not standardized either in specific soil description or in detailed accounting of lithic variation with depth. They do, however, provide a generalized view of the aquifer system, which is probably adequate for areas away from the point of major interest, and is certainly better than no data. Elevations can be estimated by interpolating the ground elevation at the well from a topographic map.

The aquifer is phreatic, principally composed of sand and gravel. There are a few places with finer material near the surface, but it doesn't con-

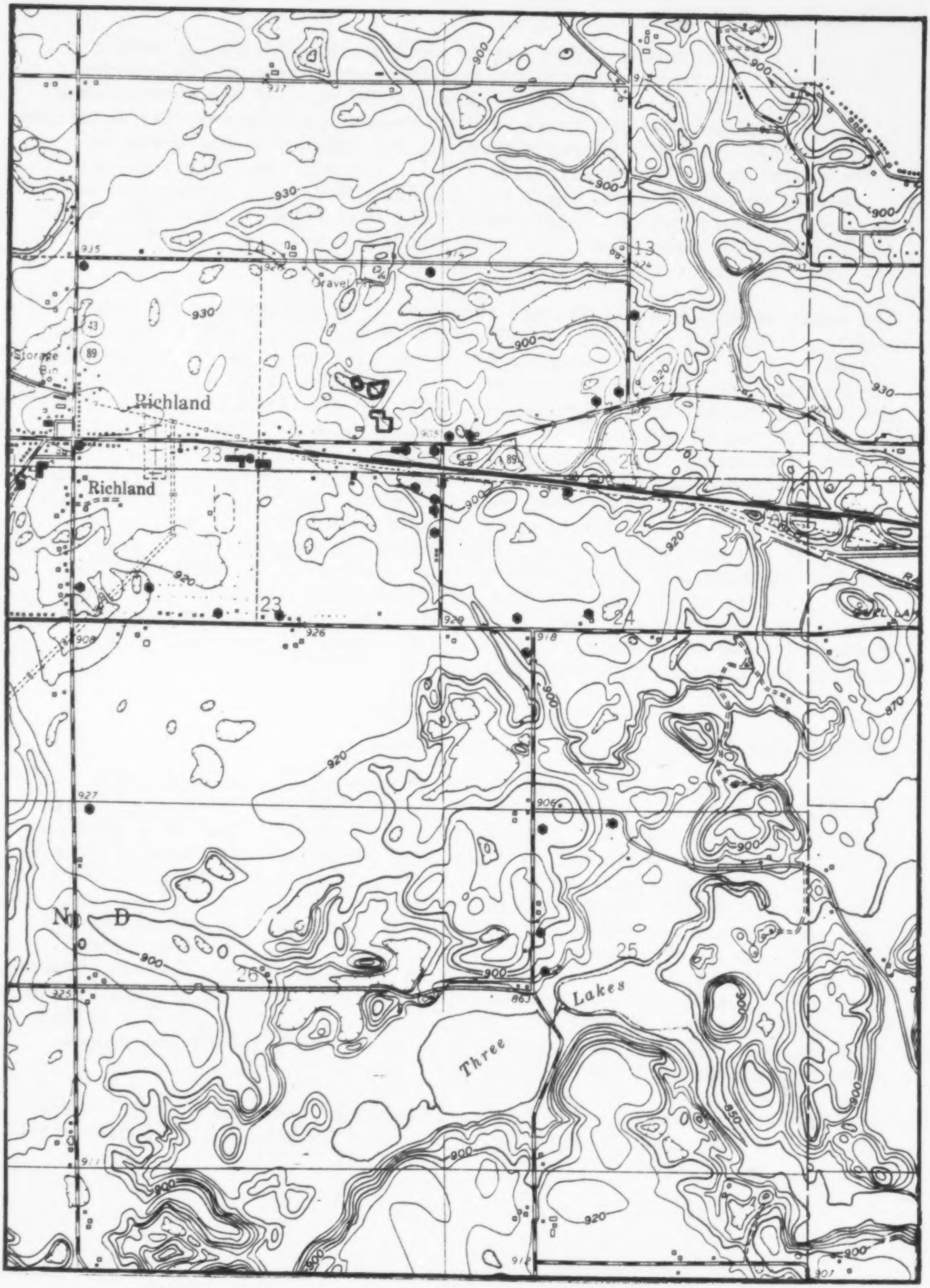
900
937
930
900
935
14
13
926
914
924
Gravel Pit
43
89
Storage Bin
930
900
920
930
Richland
905
23
89
24
Richland
900
920
920
23
24
929
926
908
918
900
870
920
927
906
900
No D
900
26
25
900
863
Lakes
Three
900
850
900
911
900
920
900
918
900
907

FIGURE 8-4 Locations of domestic wells with useful well logs.

fine the aquifer; at most it may limit recharge in those areas. An attempt was initially made to delineate the areas with the less permeable material near the surface. This was later determined to be an unwarranted and unnecessary determination. The initial recharge was estimated by a geologist to be over 6 inches/year in the sandy areas and about 2 inches/year in the less permeable areas. Aquifer bottom elevations were interpreted from the surface topography and well logs (Figure 8-5). The elevations used in the hydrogeologic study were not tied to USGS datum. The study datum was estimated by interpolating ground elevations at the wells from topographic maps. In this manner, the study datum was assumed to be 812.00' USGS. The underground troughs were assumed to roughly follow surface drainage paths.

The hydrogeologic study report indicated that there was a confined aquifer below the surface phreatic aquifer, and any leakage between the two apparently would go from the lower to the surface aquifer. Because of the relatively thick and low permeability confining layer, leakage was considered to be negligible and not incorporated into the model. Aquifer hydraulic conductivities were estimated from lab permeabilities of samples taken in the hydrogeologic study. The values ranged from 10 to 85 feet/day, with the average in the range of 40-55 feet/day. The hydrogeologic consultants (Keck Consultants) also noted that in their experience field hydraulic conductivities are frequently 3 to 5 times greater than lab tests indicate. For the initial model, the hydraulic conductivity was assumed to be in the range of 40-55 feet/day. The aquifer was assumed to be homogeneous and isotropic. Surface topography heavily influenced the estimates of the lateral boundary conditions. A chain of lakes and swamps form an arc from east of the site to the south. This is likely to be the discharge point for the aquifer. Specified heads were assigned according to the surface elevation of the lakes. No flow boundaries were assumed to follow the topographic highs, and a specified head boundary of 895' to 900' was estimated northwest of the site. This was estimated from water table elevations near the site and checked by estimating the regional gradient from Three Lakes to the site and extrapolating. These boundaries are also shown in Figure 8-5.

Production Plated Plastics monthly operating reports to the DNR of effluent quality and quantity were reviewed to estimate the amount of recharge from the seepage lagoons. The average flow to the lagoons has sharply declined in recent years:

Time Period	Average Flow (ft^3/day)
Oct. 1976 - Oct. 1977	29,000
Nov. 1977 - Aug. 1979	7,500
Oct. 1979 - Mar. 1981	5,400

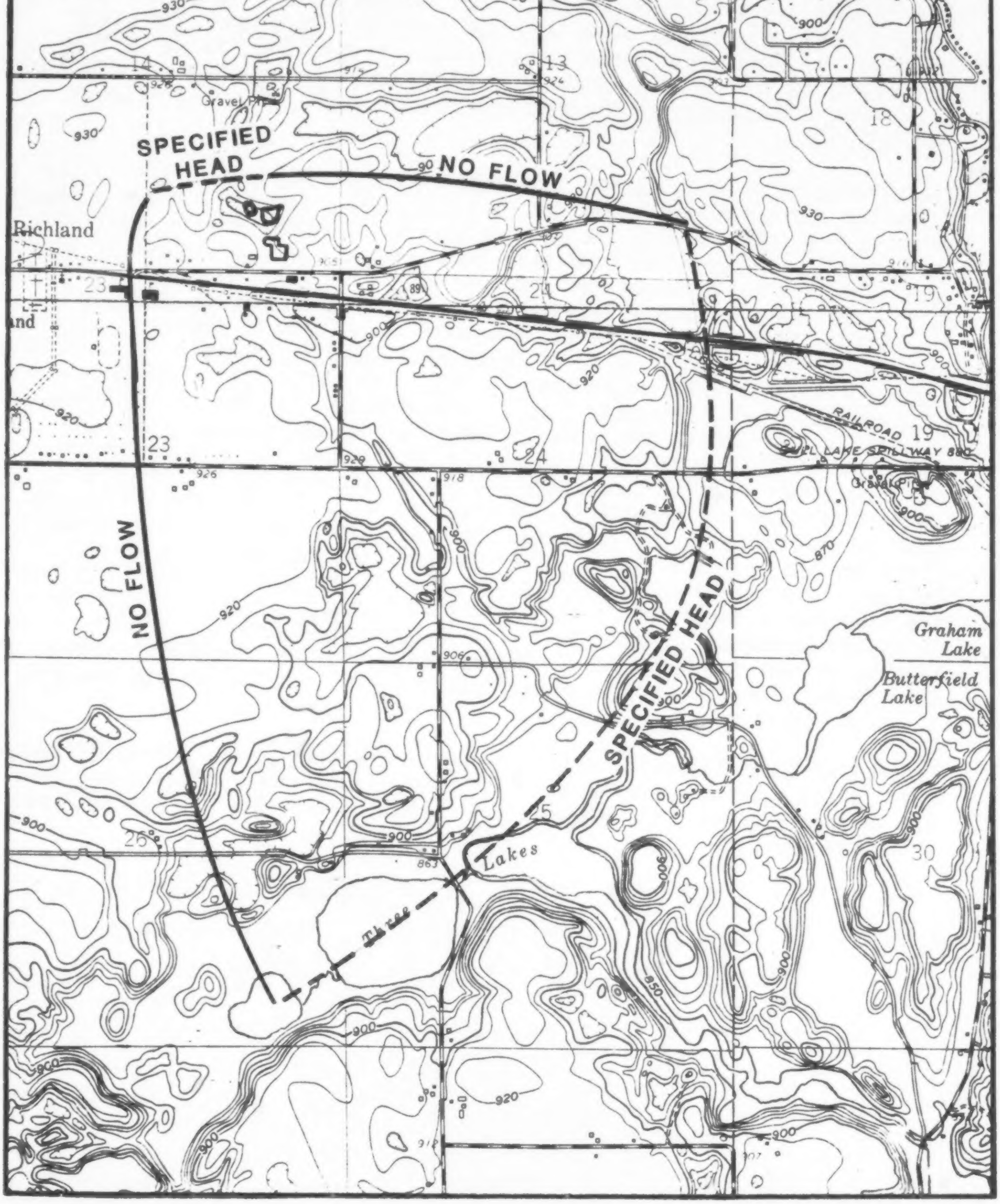
SPECIFIED HEAD
NO FLOW
NO FLOW
SPECIFIED HEAD
Richland
Gravel Pit
RAILROAD
Graham Lake
Butterfield Lake
Three
Lakes
930
920
900
870
850
14
13
18
23
24
19
25
26
30

FIGURE 8-5a Initial boundary conditions used at PPP.

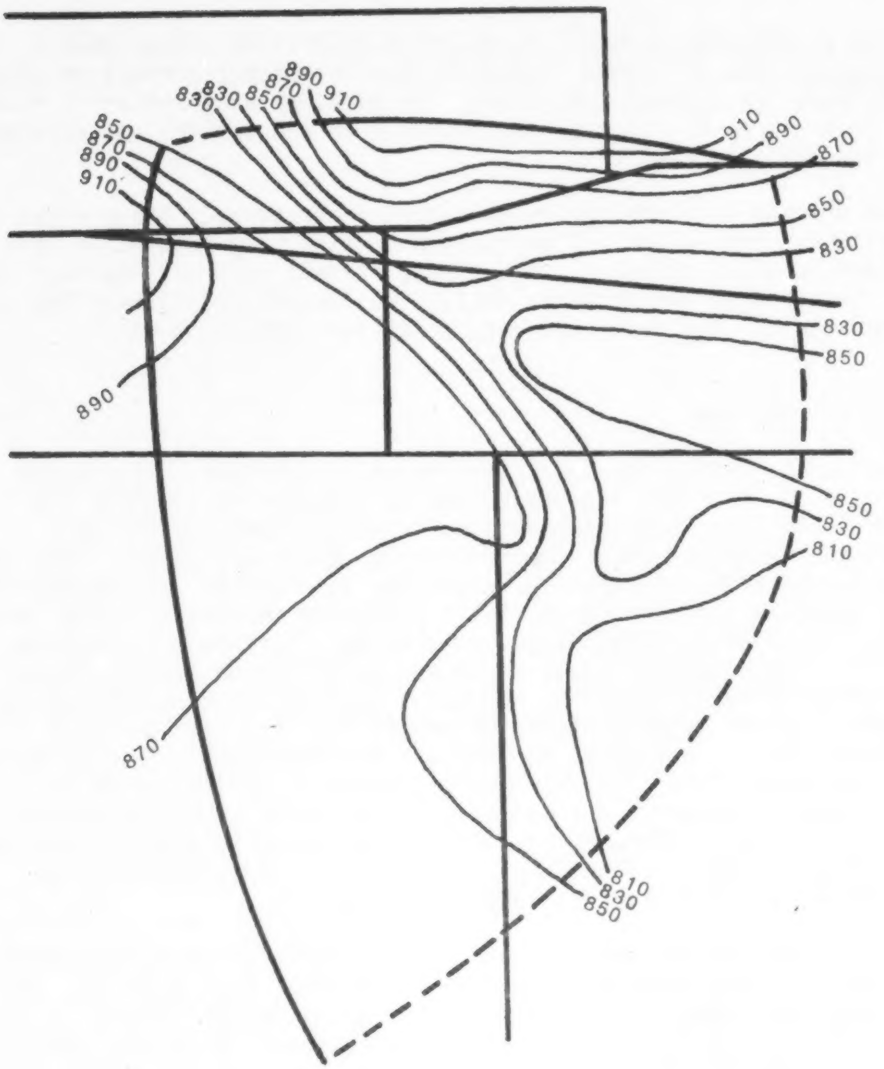
890
870
910
830
830
850
850
870
890
910
910
890
870
850
830
830
850
890
850
830
810
870
810
830
850

FIGURE 8-5b Initial aquifer bottom elevations.

Most of the simulations were of steady state conditions. They used a lagoon recharge rate of either 29,000 ft^3/day for higher production times or 6600 ft^3/day for current conditions. In Michigan evaporation is roughly equal to rainfall over a year so the recharge to the aquifer was assumed to equal the effluent discharge.

The buried troughs were thought to be important features. There might be significant "channelization" of the groundwater flow that would have a big effect on plume movement. The finite element grid was designed to carefully incorporate the troughs, include sufficient detail near the site, and incorporate all the above boundary conditions (Figure 8-6).

Flow Model Calibration

This first model formulation had severe boundary problems. An attempt had been made to literally include enough information to simulate the aquifer pinching out. Bottom elevations in nodes along the northern boundaries were assigned above the known water table elevation. This caused endless problems with the numerical algorithm in AQUIFEM. The boundaries had to be moved to a point with a finite saturated thickness. Once this problem was eliminated, sensitivity analyses were performed by varying: the hydraulic conductivity, areal recharge rates, lagoon loading rates, and the specified heads along the northwest boundary. The model was calibrated against water table contours developed from the hydrogeologic study (Figure 8-7). There were problems in matching these contours with the flows generated from areal and lagoon recharge, and the range of hydraulic conductivities used. To match the contours it was necessary to force water to exit through the northwest boundary by drawing down the specified heads to 886'. This simulation used K = 40 ft/day, original areal recharge, and 6600 ft^3/day lagoon recharge.

An excellent match of the observed and simulated water table elevations was obtained (compare Figures 8-7 and 8-8). However this match was deceptive, and there were a number of problems with the simulation. A large flow (6700 ft^3/day) exited the system to the northwest with only about half as much (3400 ft^3/day) passing through southeast of the lagoon. This did not seem to be reasonable, since there has been no evidence of this much flow or accompanying contamination moving to the northwest. Flow moving toward residential wells southwest of the site had a simulated velocity of .3 to .5 feet/day. This results in a travel time of about 15 years from the suspected source to the affected domestic wells, much longer than would be possible, although higher lagoon loadings in the past could have caused a steeper gradient and higher velocities.

Since the specified head boundary northwest of the site was forcing the solution, and the boundary behavior and heads were not well defined, it was decided to find an alternate boundary. No flow boundaries were estimated following surface topographic highs (Figure 8-9). For the first

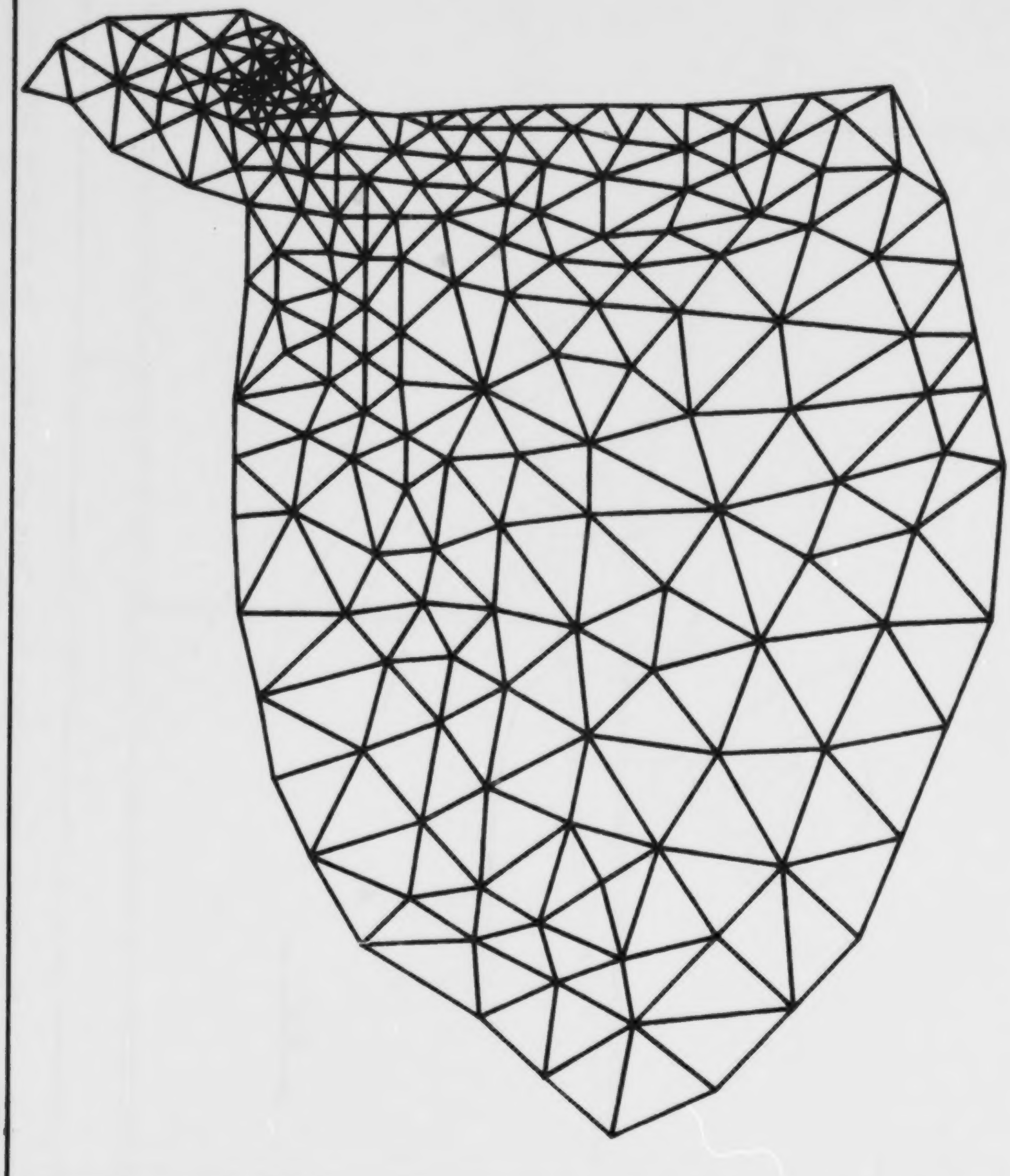

FIGURE 8-6 First finite element grid used at PPP. Parts of the northern and western boundaries were moved in because of numerical problems caused by dry nodes in these areas with high aquifer bottom elevations.

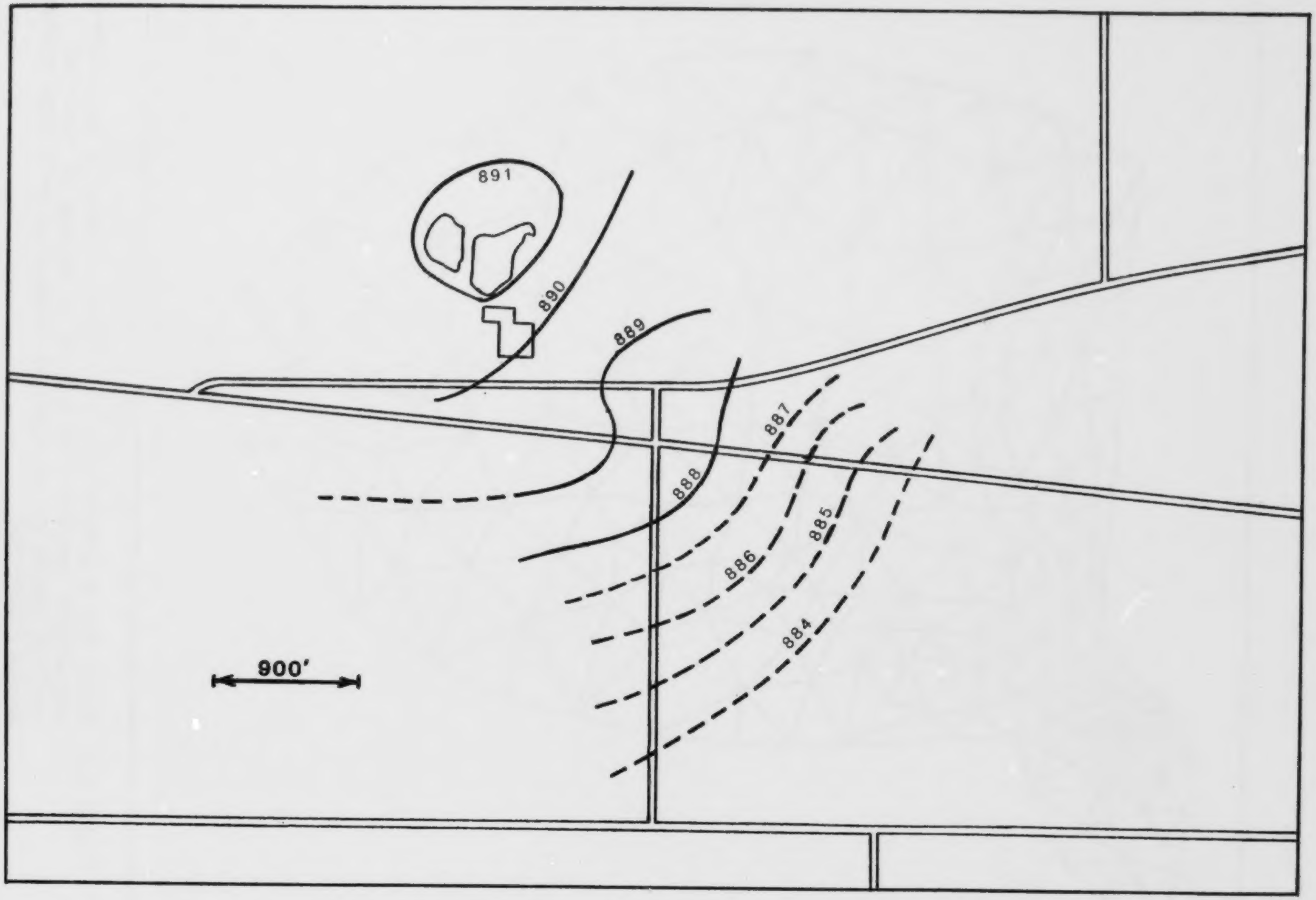
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FIGURE 8-7 Piezometric head contours from field work (1980). The elevation datum was not known at the time. It was estimated to be 3 feet lower than the actual values here.

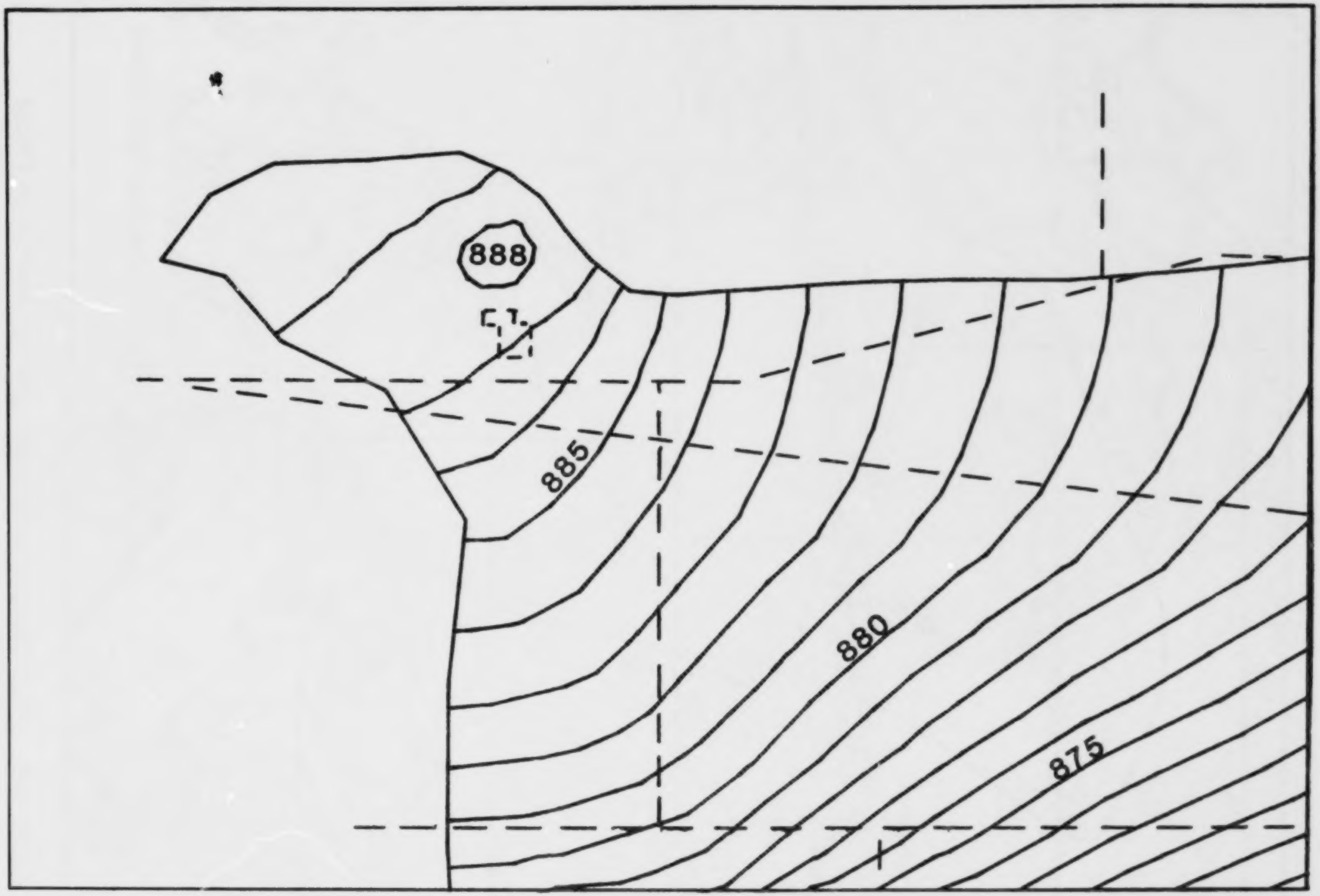

FIGURE 8-8 Early simulation results that very closely fit the observed data. However the boundary conditions northwest of PPP was artificially "forcing" the fit.

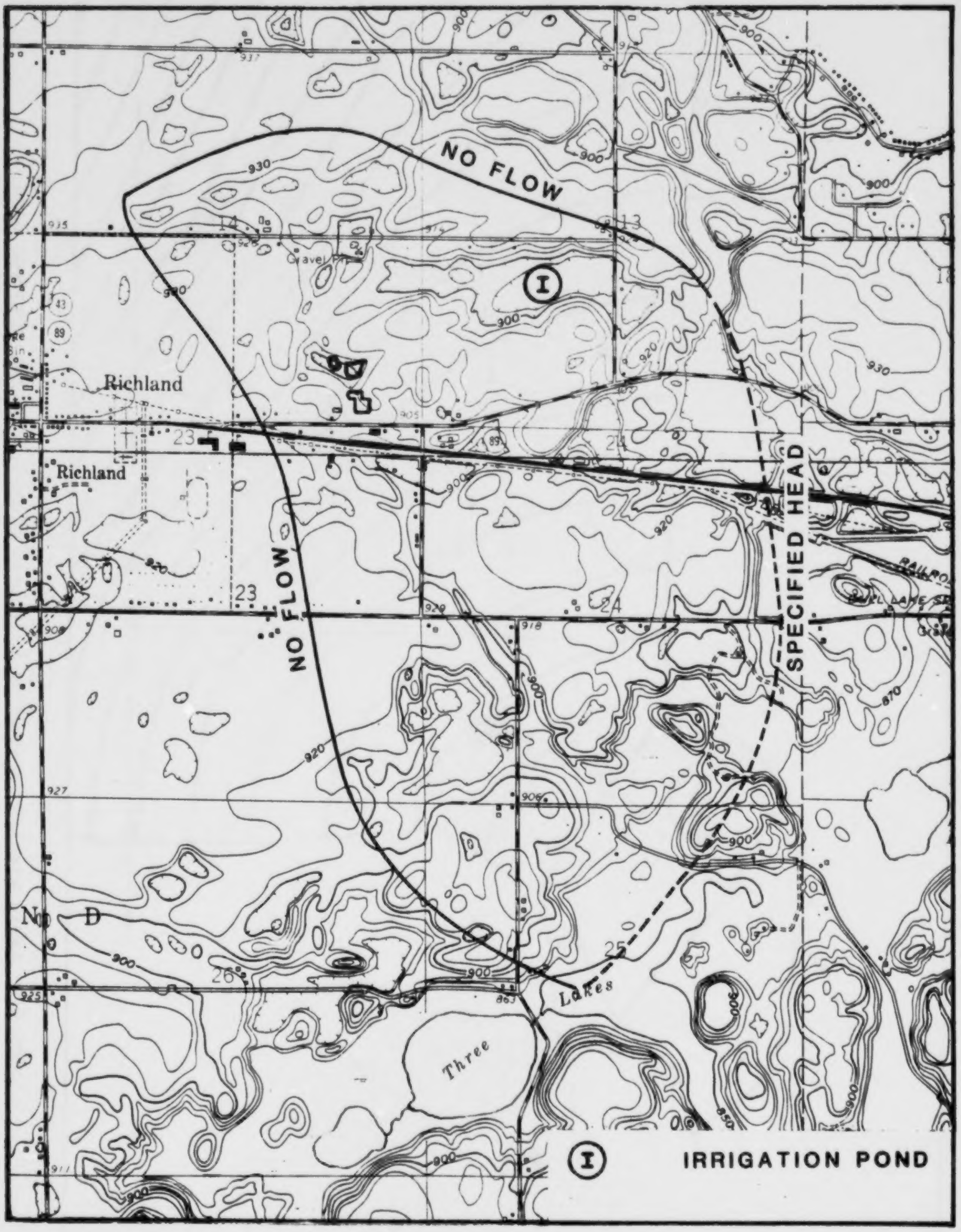
NO FLOW
NO FLOW
SPECIFIED HEAD
Richland
Richland
Gravel Pit
Three
Lakes
IRRIGATION POND
930
920
900
905
910
925
927
937
935
911
918
906
865
870
850
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FIGURE 8-9a Final boundary conditions used for Production Plated Plastics.

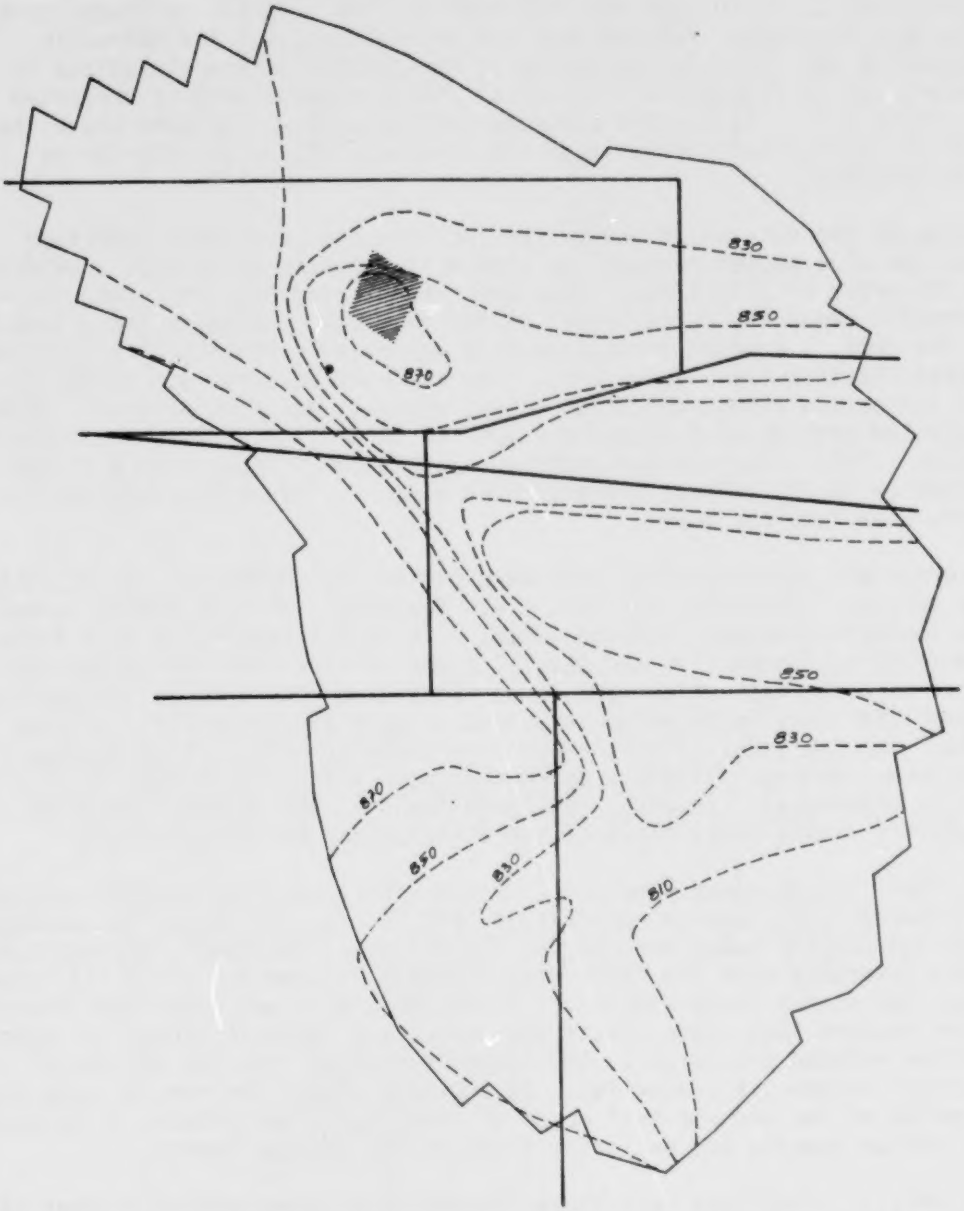
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FIGURE 8-9b Aquifer bottom elevation contours. The shaded area is an interior no flow boundary where the aquifer pinched out.

few simulations the only hydraulic connection to the northern extension was assumed to be through the area that was the original northwest specified head boundary. Results were not satisfactory, so the hydraulic connection was increased by modifying the aquifer bottom elevations to those shown in Figure 8-9. The final finite element grid is presented in Figure 8-10. It has 424 elements and 234 nodes. The area where the aquifer pinched out northeast of the site was left as an interior no flow boundary.

Review of the data collected by the local health department indicated that the slug passed through the area with domestic wells with a velocity on the order of 1 foot/day. With the current gradient, this requires a hydraulic conductivity in excess of 100 feet/day. During a field inspection of the area, a dredged irrigation pond was noted northeast of Production Plated Plastics (see Figure 8-9). Several hundred acres are irrigated and irrigation withdrawal might affect the regional flow pattern. Records indicated that about 6 inches are applied to 300 acres during the growing season. This is an average withdrawal of 73,000 ft^3/day over a 90 day period or 18,000 ft^3/day averaged over a year. This withdrawal was incorporated into the model.

A series of sensitivity analyses were performed. Hydraulic conductivity was varied, ultimately setting K = 120 feet/day. This is several times the laboratory values, but consistent with Keck's experience that field hydraulic conductivities are several times greater than laboratory results. Areal recharge was varied, and comparisons were made between designating higher and lower recharge areas versus using a single uniform recharge rate. For the final solution a uniform recharge rate of 8 inches/year was used. Several different approaches were tried to simulate the irrigation withdrawal: pumping, specified heads at the lagoon, and using AQUIFEM's rising water table or specified ground elevation option.

The final steady state simulation used K = 120 feet/day, uniform recharge of 8 inches/year, lagoon recharge of 6600 ft^3*/day and irrigation withdrawal from two pumping nodes totaling 18,000* ft^3*/day.* The model response compared favorably with the field data (compare Figures 8-7 and 8-11). However, the steady state simulation values were 2-3 feet lower than observed. Other factors that could affect the values are seasonal irrigation pumping and the reduced discharge to the lagoon resulting from the decline of American automobile production. An unsteady simulation run was made over a period of two and one-half years to investigate the effects of seasonal irrigation pumping and declining flows to the seepage lagoons.

The initial conditions were those assumed to be prevalent in October 1977. An initial steady state flow field was based on high production lagoon recharge rates and annual average withdrawal from the irrigation pond. During the simulated two and one-half year period, the lagoon recharge rates were periodically lowered as indicated by PPP's Monthly Operating

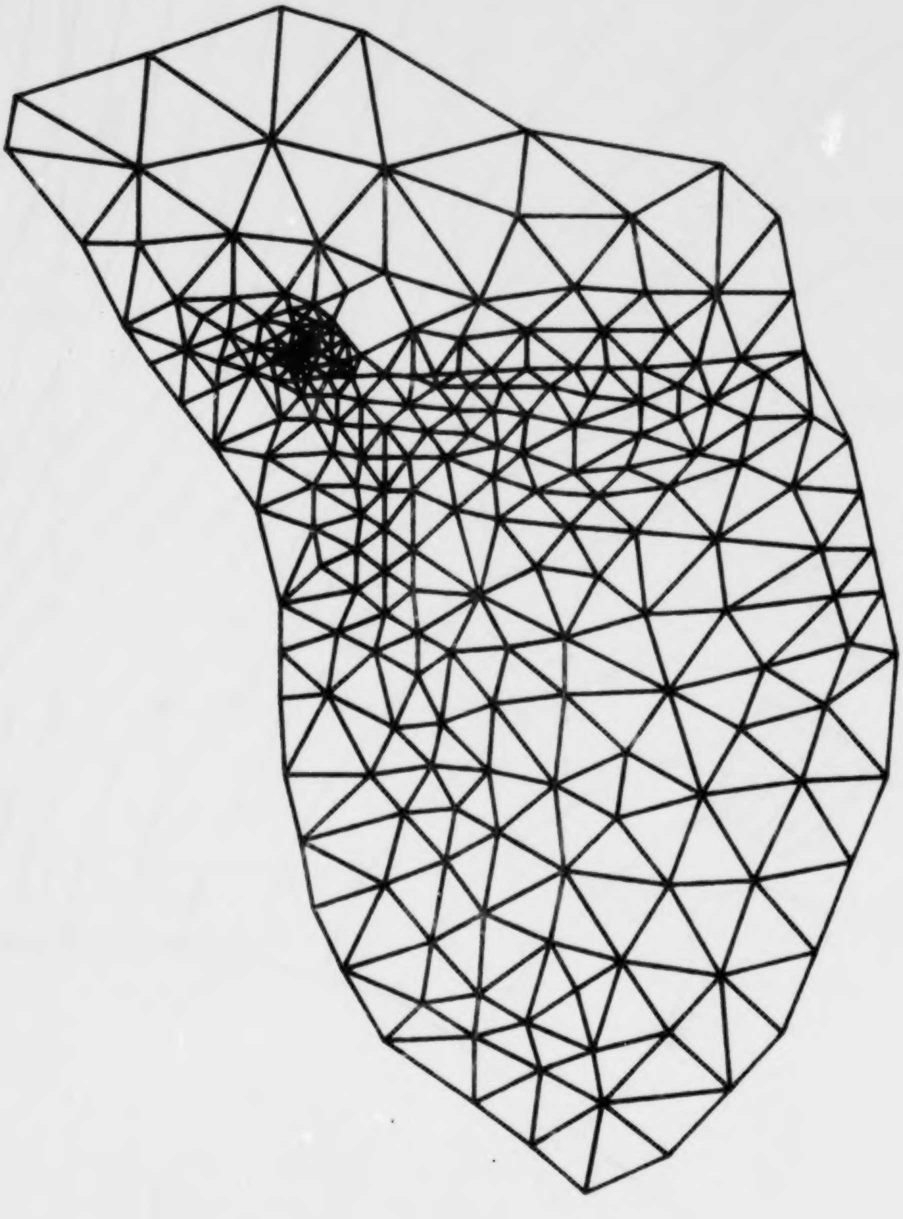

FIGURE 8-10 Final regional finite element grid used at PPP.

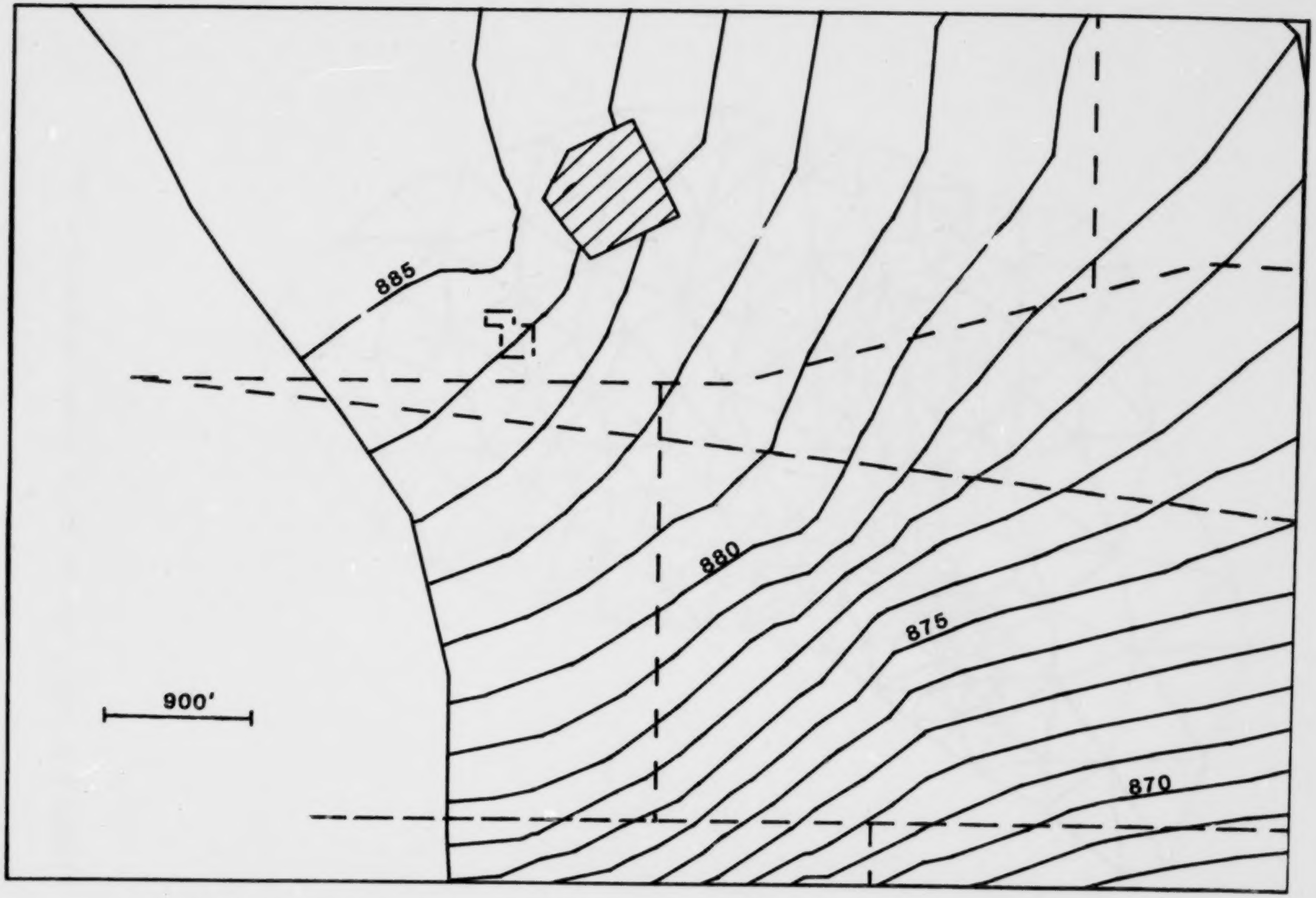

FIGURE 8-11 Simulation piezometric heads for conditions known before field work resumed in May 1982. The datum for the field measurements was not known at the time. This simulation was attempting to match values that were thought to be 3 feet lower than those shown in Figure 8-7.

Reports and irrigation water was withdrawn only during the summer months. The simulated piezometric contour map for October 1977 is shown in Figure 8-12, and the result after simulating 2.5 years (April 1980) is shown in Figure 8-13.

The results indicated that it was reasonable to expect the observed values to be about two feet higher than the conditions used for the long term steady state simulation. The unsteady simulation seemed to give a very realistic system response and increased the overall confidence in the model.

Mass Transport Models

The other component in the study is contaminant or mass transport modeling. This type of modeling is far more complex and not as well developed as flow modeling. Transport models are used to try to account for dispersion/diffusion or mixing of the contaminated plume with the surrounding water as well as for some soil-contaminant interaction.

While transport models cannot be considered highly accurate, they do indicate trends, aid in understanding and interpreting the physical situation, and can provide valuable input into the management decision process. Both analytical and numerical models are being applied at Production Plated Plastics. The models are used to estimate where the plume may now be located, and what its fate might be. When additional field work was started, the model helped direct that work. New data provided by field work was used to update the model. The models will be able to assist in designing and evaluating remedial action plans.

Parameter Estimation

It is difficult to estimate the parameters needed for a mass transport model. Several important types of information are ideally required to analyze a plume: its areal distribution; a record of its changes with time; definition of the contaminant source (location, strength and duration); description of any interaction between the contaminant and soil matrix; and definition of the groundwater flow system (especially seepage velocity distribution). This information is usually scarce to non-existent when the DNR begins to work on a contamination problem. From borings and resistivity surveys the areal distribution of the plume can be determined. The same information can be used in the flow modeling process, as previously described, to estimate the flow field and velocity distribution. Sampling is usually not continued systematically over a long time interval so the plume movement is not documented. Little is usually understood about interaction between the contaminant and soil matrix. And there is usually little information available regarding the source. The source location can usually be found, but the strength and duration are usually matters of speculation.

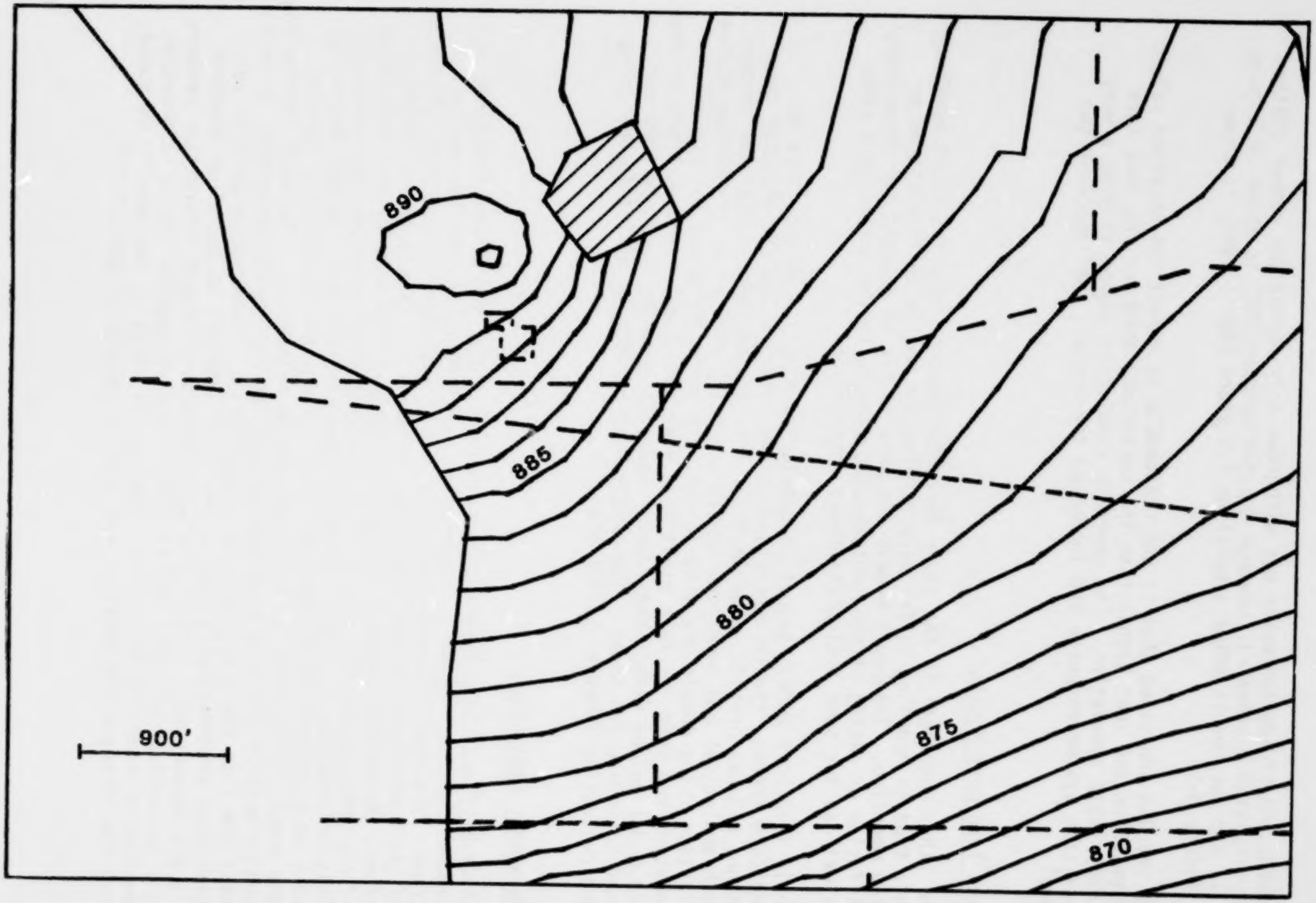
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FIGURE 8-12 Steady state conditions assumed to represent October 1977 conditions. These were used as initial conditions for the unsteady state simulation.

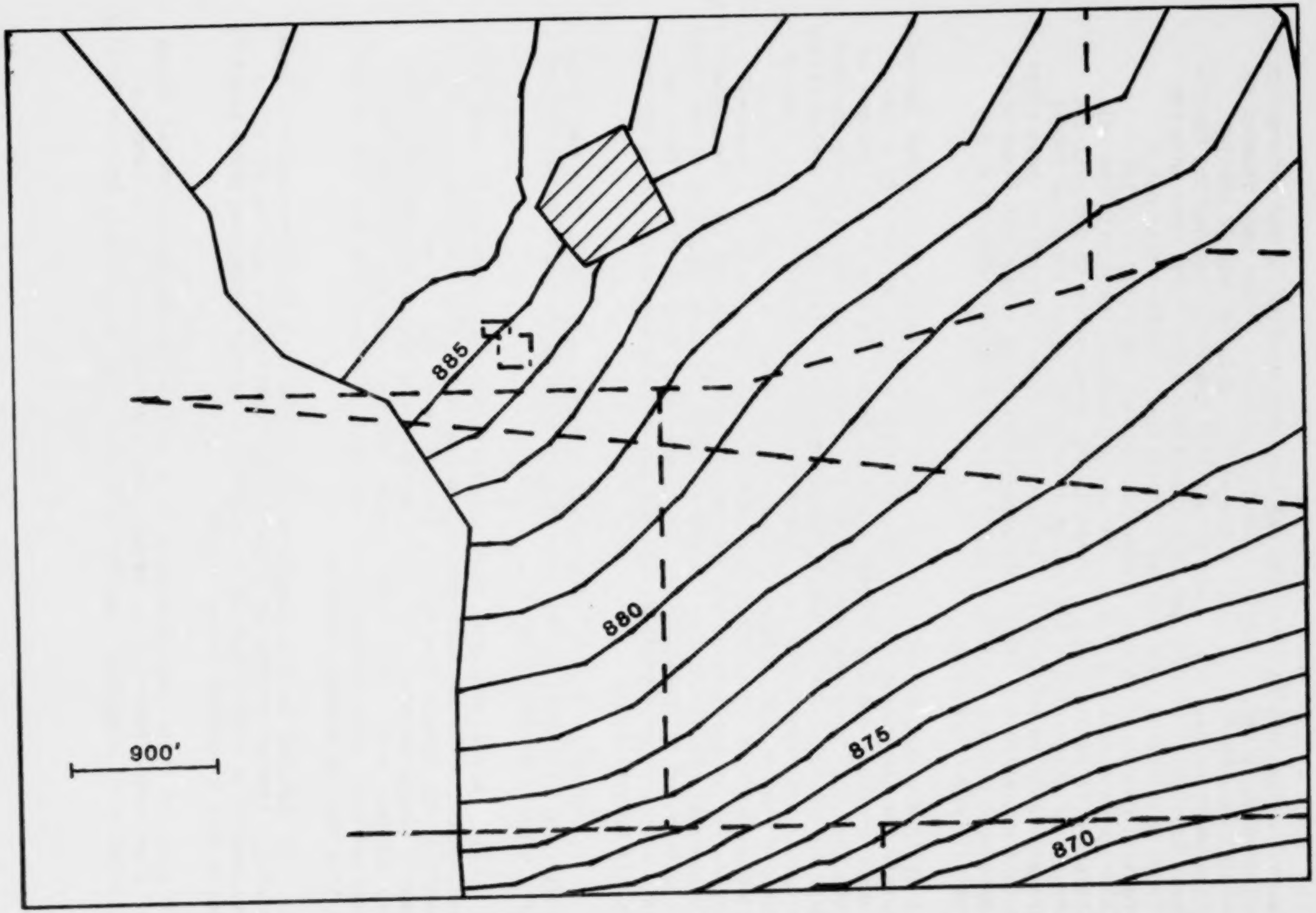
885
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FIGURE 8-13 Piezometric head contours after a simulation of 2.5 years of unsteady state conditions.

Several contamination sites the DNR has been involved in had information defining the plume, including some time history. These were studied to develop parameters from sites where we have data for use in similar sites where we have none. Dr. Wright from the Civil Engineering Department, University of Michigan, analyzed these sites. Two were chloride plumes originating from road salt stockpiles. Another site was a chemical company with many contaminant plumes including chloride. Chloride is a conservative substance that doesn't react with the soil. Therefore it is useful as a tracer in the groundwater to evaluate the effects of dispersion. Not enough information about the plume fronts was available to estimate the longitudinal dispersivities at these sites. Wright estimated the lateral dispersivities using a Gaussian Plume model. Appendices B and C contain Wright's reports with full details of his analysis and conclusions.

It is interesting to note that the three sites studies all yielded approximately the same value for the lateral dispersivity, at least to within a factor of four, ranging between 5 and 20 feet. It also is of interest to note that they were derived from fairly similar problems; all the aquifers were 50-100 feet thick, classified as sandy aquifers, and the contamination problems had roughly the same concentrations of chlorides. *This tends to support the concept of being able to apply results from one aquifer to another one that is similar, at least when the problem is on a regional scale.* It is possible in all of the situations analyzed that the dispersivity is somewhat overestimated. In the analysis, all the spreading of the plume is attributed to dispersivity. There are other factors that affect the interpretation of the plume size and may cause dispersivity to be systematically overestimated.

1) Although density effects are probably very small, they may cause additional spreading in the lateral direction, which would be attributed to a greater dispersivity.

2) The analysis used plume contours that were provided by other investigators. The contours probably overestimate the plume extent. For example, the person drawing in a contour (e.g. the 250 mg/l contour) will nearly always encompass all wells which have a higher concentration than the contour level. This often results in many readings less than the contour level also falling within the contour extent and does not reflect a true average contour location.

3) Related to this consideration is the fact that frequently no data giving a lateral profile at a particular location are available. It is reasonable to expect that if this detail were available, the plume boundary would have a narrower actual width.

In spite of these considerations, it is logical to use the estimated values of transverse dispersivity, rather than the true ones, in any numerical simulation of a regional aquifer problem. This is precisely because density effects are generally ignored in two dimensional simulations and it is also generally desirable to know the probable maximum lateral extent of the contaminant plume which does involve all of the unknown flow path variations that have not been considered in the above analyses.

Longitudinal Dispersivity Determination at PPP

The discussion immediately above is partially intended as a preface to the presentation of the longitudinal dispersivity determination at PPP. Data for this site are significantly different than for the three previous sites. The fact that individual observation well data (point data) are analyzed here more than likely results in lower estimates of dispersivity due to the reasoning presented in explanations 2 and 3 above. Chromium contamination was found in several domestic wells downgradient from Production Plated Plastics. The wells were monitored for over a year by DNR and the Michigan Department of Public Health. Well locations may be found in Figure 8-2. Total chromium concentrations found in several wells are listed in Tables 8-1 and 8-2. Results from wells V-1, WM-1 and WG-1 appear to represent a slug passing through that area. Well G-1 also showed high chromium values. The flow direction determined from the hydrogeologic study by Keck Consulting Services and subsequent model analysis indicate that the source affecting G-1 is a separate incident from the source affecting the other wells.

From the time history of the chromium concentrations in wells V-1, WM-1 and WG-1, Wright was able to estimate the longitudinal dispersivity. The dispersivities were estimated by using a Gaussian Plume model. Normal distributions were fit to the observed concentration profiles and various simplifying assumptions were made regarding the nature of the groundwater flow that can be extracted from the available data. Details of Wright's work may be found in Appendix C.

The longitudinal dispersivity was estimated to be 2 feet. This is considerably smaller than the values estimated previously for lateral dispersivities. Part of the reason may be the fact that the estimates in this case are from point measurements and that all of the effects of using a number of wells to define a plume are not considered. In general, it should be anticipated that longitudinal dispersivities should be greater than lateral ones in a given aquifer as long as the medium is isotropic. Since the travel distances are not significantly different than the other sites considered and the gross aquifer characteristics are not apparently much different, perhaps it should be concluded that the medium is more homogeneous than in the other cases.

Wright felt that a realistic estimate of field dispersivities has been obtained in this study. Consultation of the literature yields a wide range of values depending upon the methodology employed. The paper by Pickens and Grisak (1981a) gives a good summary of several previous studies.

TABLE 8-1

Total Chromium found in Domestic Wells near Production Plated Plastics
(parts per million)

	Well Code						
Date	A-1	F-1	G-1	V-1	WM-1	WG-1	B
6-8-77	0.12	0.08	3.0				
8-22-77	0.12		2.9	9.1			
8-31-77		0.33			0.8	0.04	
9-19-77					2.5	0.11	
10-18-77	0.14	0.02	1.1	11.0	5.6	0.6	
12-6-77	0.20		1.2	6.4	1.9	1.4	0.34
1-11-78	0.23	0.01	0.62	2.2	5.0	4.2	0.30
1-23-78							0.32
3-1-78							0.32
3-27-78	0.28	0.01	0.38	0.67	6.0	3.5	
6-13-78	0.33	< 0.01	0.16	0.23	7.8	3.6	
7-20-78	0.37	0.01	0.15	0.16	11.0	7.0	

TABLE 8-2

Total Chromium found in Monitoring Wells around Production Plated Plastics
(parts per million)

Well	June 1979	March 1980	April 1980	May-July 1982
			Date	
Keck-1	.067		.05	<.01
Keck-2	.068		.04	.109
Keck-3	.23	.09	.06	0
OMW-1	.085			
OMW-3	.027		0	
OMW-4	.87	.09	.01	.03
OMW-5	.26			
OMW-6	.26	.14	.07	
Lagoon-1	.12			
Lagoon-2	.11			
WW-2	.33			
WW-4	20.			
WW-8	.005			
WW-9	12.			
OW-1s		0	.06	.07
OW-1d		0	.07	
OW-2s			.02	0
OW-2d			.01	.23
OW-3		.28	.01	
OW-4		.54	.12	
OW-6		.1	.06	0
OW-7			.08	<.01
OW-8s			.02	
OW-8d		.04	.07	
OW-10			.07	<.01
OW-11			.07	.14
OW-12			2.73	.103
OW-13			1.53	2.3
OW-14			.06	.14
OW-15			.11	0
OW-16			.05	.02
KW-4				<.01
KW-5				<.01
KW-6				2.1
KW-7				<.01
KW-8				2.8
KW-9				.03
KW-10				.076
KW-11				2.2
KW-12				.24
KW-13				.16
KW-14				.19
KW-15				.03
KW-16				.03
KW-18				.06

Generally, dispersivities estimated by fitting data by numerical solutions are larger than those obtained in the present study. This is to be expected, since the numerical solutions effectively require the dispersivity to make up all of the ignorance in actual source conditions. This is especially so with longitudinal dispersivities. On the other hand, pumping tests often result in lower dispersivities than computed herein. This can be expected for two reasons: 1) the relatively smaller scale of the experiments and 2) the fact that these are point measurements. The implications of this second factor were discussed above and the first simply reflects the known condition that dispersivities exhibit some dependence upon the physical scale of the system (Pickens and Grisak suggest the longitudinal dispersivity to be a linear function of distance at small scales). Thus, the values obtained fall generally within a range that may have been anticipated at the outset of the investigation, although the results for PPP may be somewhat low for what might be expected. *Considering the relative uncertainties of these estimated quantities and the implications as compared to other uncertainties, (for example in hydraulic conductivities) it is clear that any dispersivity of the correct order of magnitude should be acceptable in a numerical simulation. Given this consideration, the results of this study should be applicable to other related sites in the state, at least for circumstances where data are not available from which to make an estimate.*

Analytical Mass Transport Model Application

Analytical mass transport models were used as a first step in studying plume movement. Modified versions of Cleary & Ungs' 2-D and 1-D mass transport models were used. The principal input parameters are longitudinal and lateral dispersivities, and seepage velocity. Dispersivities were estimated by Wright. Flow paths and seepage velocities were determined from AQUIFEM. Seepage velocities were averaged along a streamline to estimate the constant seepage velocity used in the analytical models. In reality, and as shown in the AQUIFEM model, velocity variation is to be expected along a streamline. Three streamlines originating from the lagoons are shown in Figure 8-14. A slightly conservative average seepage velocity of 1.4 ft/day was initially used. A longitudinal dispersivity of 5 feet was used; therefore, the longitudinal dispersion coefficient was 7 ft^2/day (1.4 ft/day x 5 ft.). The lateral dispersion coefficient was assumed to be 2 ft^2/day, in the range of 1/3 to 1/5 of the longitudinal value. The source was assumed to be 250 feet wide, with a duration of 90 days. Several sensitivity analyses were made to investigate the effects of various assumptions made.

As the plume moves downstream, its peak concentration decreases and it lengthens and widens from the effects of dispersion. This is clearly shown in Figure 8-15. The relative concentration (C/C_0, where C_0 is the initial concentration) is plotted against distance from source, at different times.

The dispersion coefficient has a strong influence on the plume shape. Three longitudinal cross sections at t = 1500 days are presented in Figure 8-16 for widely different dispersivities. A dispersivity of 5 feet is the order

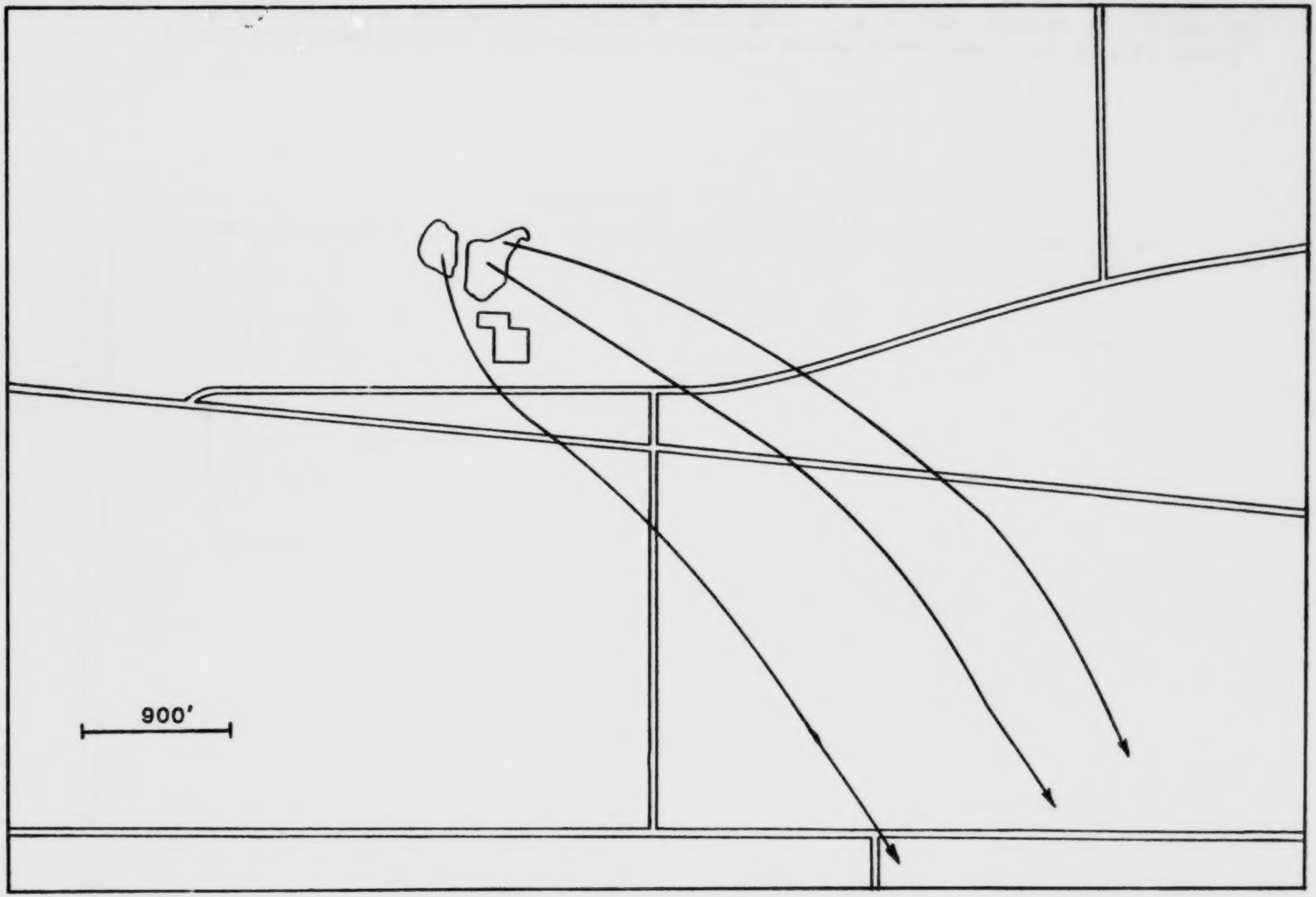

FIGURE 8-14 Example streamlines originating from lagoon based on simulation of 1980 data.

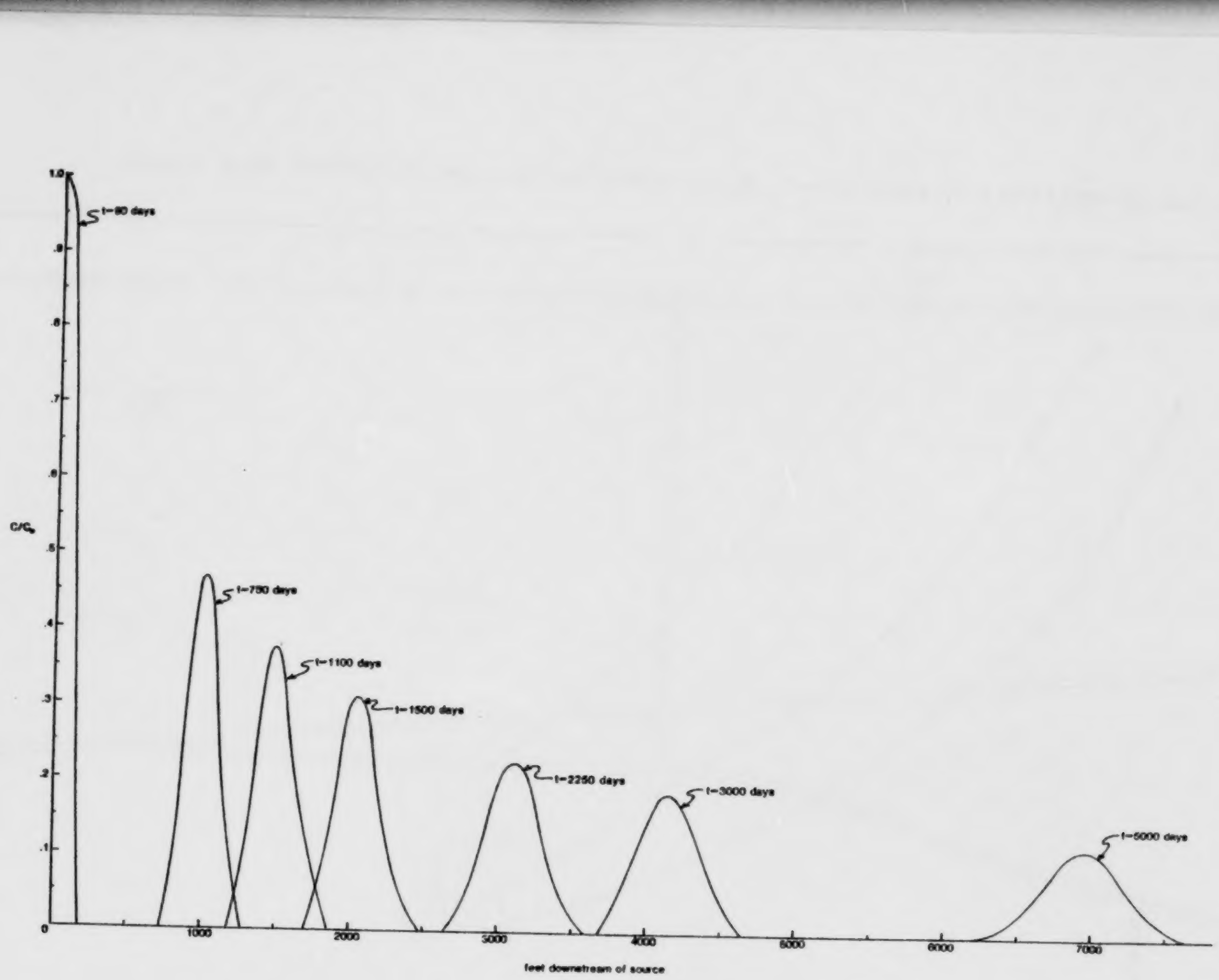

FIGURE 8-15 Longitudinal cross section of a plume moving downstream. The initial source is 250 feet wide and the slug duration is 90 days. The seepage velocity is 1.4 feet/day with α_L = 5 feet, the dispersion coefficients are DX = 7 ft^2/day and DY = 2 ft^2/day.

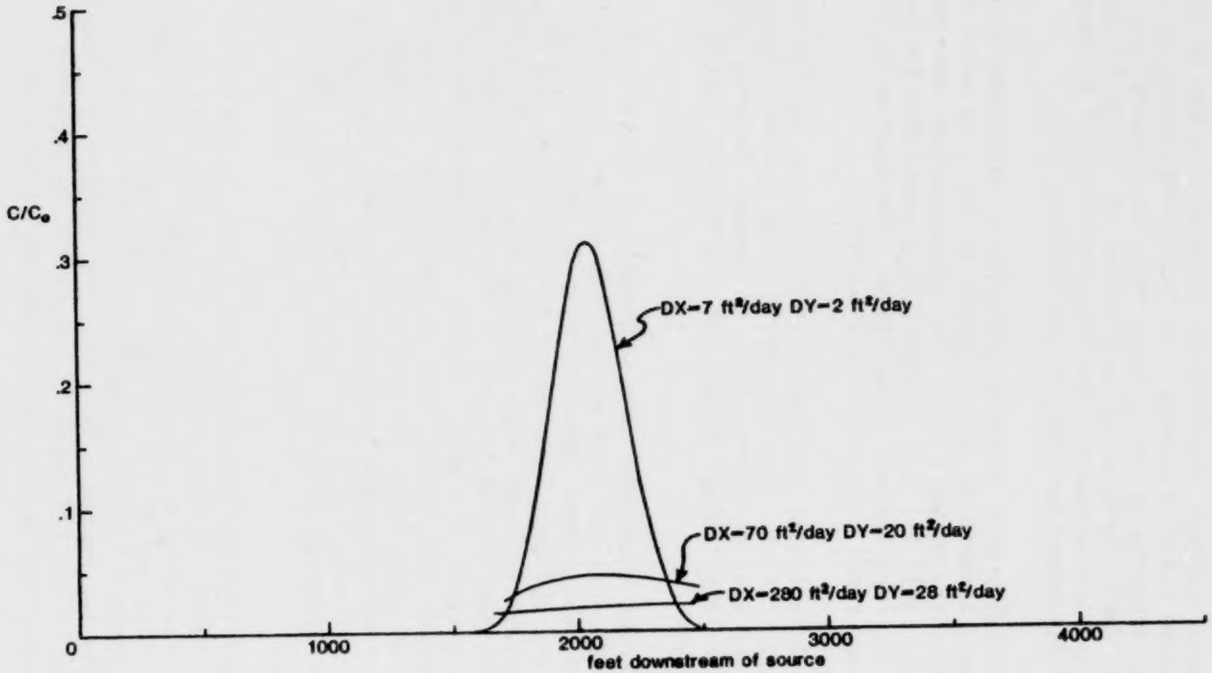

FIGURE 8-16 Longitudinal cross sections for range of dispersivities at t = 1500 days for a slug duration of 90 days and seepage velocity = 1.4 feet/day.

of magnitude found by Wright in analyzing the plume. A dispersivity of 50 feet is more on the order that Wright estimated for the Story-Ott Chemical site. Pickens and Grisak (1981a) indicate that dispersivity is scale dependent and based on their field study of plume movement over several meters, suggest longitudinal dispersivity may be estimated as 10% of the mean travel distance. If this relationship is valid up to the distance traveled by this plume, then the dispersivity is on the order of 200 feet. Lateral dispersivities of 1/3 to 1/5 longitudinal dispersivities were assumed. The dispersivities of 50 feet and 200 feet are clearly not characteristic of the observed slug.

Analytical results were directly compared to measurements at well V-1. Dispersion was assumed to be negligible as the slug moved through the immediate vicinity of well V-1. The concentrations were normalized, C (C peak) for well V-1 and $((C/C_0)/(C/C_0)$ peak) for the analytical model, to compare the longitudinal plume shape. The best match (Figure 8-17) required a very small dispersivity (1.5 feet).

Figure 8-18 illustrates the impact of dispersion coefficients on the plume's lateral cross section. Smaller coefficients maintain a higher peak concentration and smaller plume width. A greater lateral dispersion coefficient with the same longitudinal dispersion coefficient results in a lower peak and wider plume.

Nothing is known about the source strength or duration at PPP. An arbitrary duration of 90 days was used as the base value. A sensitivity analysis was performed to investigate impact of this assumption. Slug durations ranging between 10 and 180 days were run at t = 1100 days, see Figure 8-19. Shorter durations result in lower peaks because less mass is injected into the system. The peak time also shifts because of the change in the centroid of the slug mass, although this is a minor effect. If the different durations are compared on a normalized basis, then it can be seen (Figure 8-20) that the shapes are the same, only the timing is slightly changed. Since our only information involves plume shape and not source description, the slug duration used in the analysis is not critical. The important factors are dispersivity and seepage velocity, both of which were estimated from field observations.

A final comparison was made between 1-D and 2-D analytical model results. Figure 8-21 shows the slug profiles at t = 1100 days for a 90 day slug source duration using a 1-D analytical model and separate runs with DX = 2.1 ft^2/day and DX = 7 ft^2/day. A 2-D analysis with the same input, except including a lateral dispersivity of 0.5 ft^2/day, was only slightly less than the 1-D result. The peaks are relatively close because the lateral dispersivity in the 2-D model is so small. As expected, 1-D peaks are higher because they do not include lateral dispersion.

Many runs can be made with the analytical models in very little time and for little money. A simplified but very useful analysis of the effects of dispersion can be quickly made. Sensitivity analyses help the investigator develop a better "feel" for the relative importance of the parameters and a better idea of the possible system behavior.

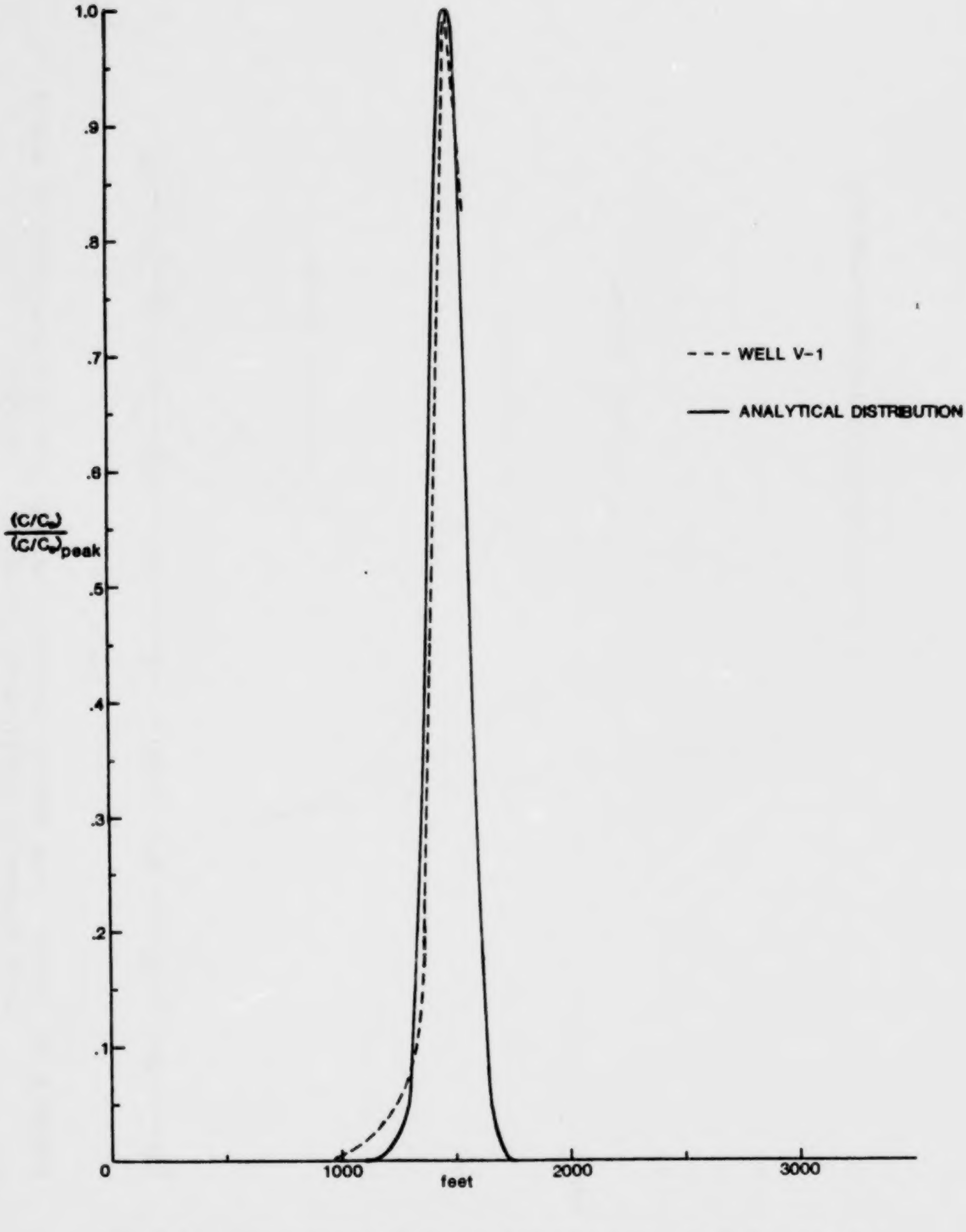

FIGURE 8-17 Comparison between observed plume shape in Well V-1 and analytical solution with α_L = 1.5 feet.

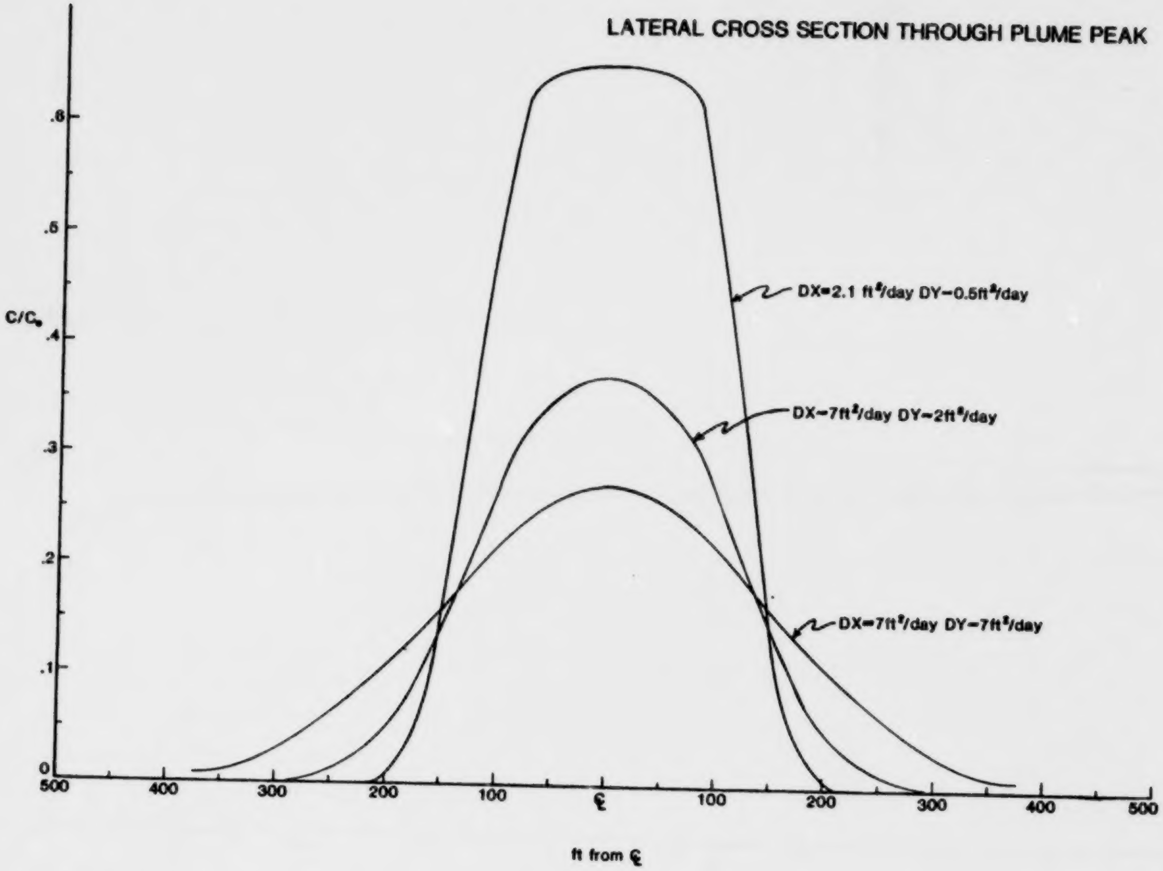

FIGURE 8-18 Lateral cross section through plume peak 1475 feet downstream of source with dispersion coefficients varied, t = 1100 days.

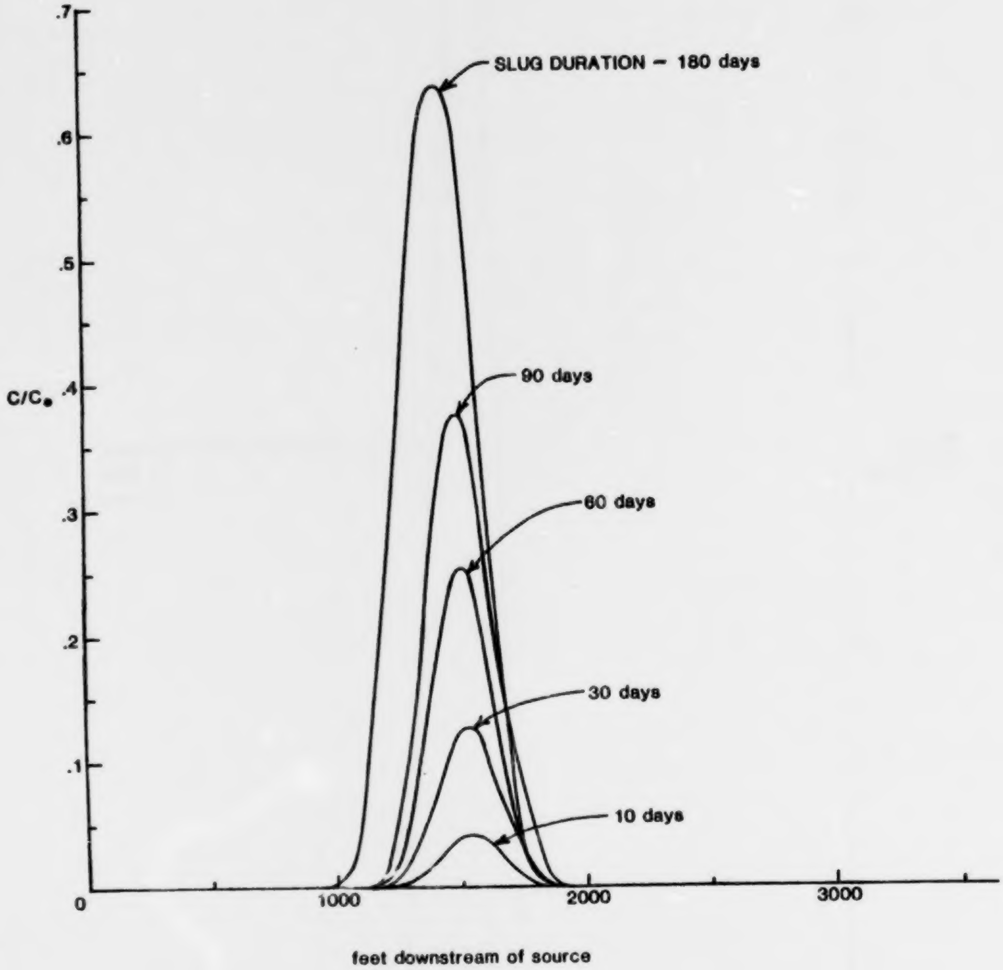

FIGURE 8-19 Slug duration sensitivity analysis. Longitudinal cross sections at t = 1100 days using a source width of 250 feet, seepage velocity = 1.4 feet/day, DX = 7 ft^2/day and DY = 2 ft^2/day.

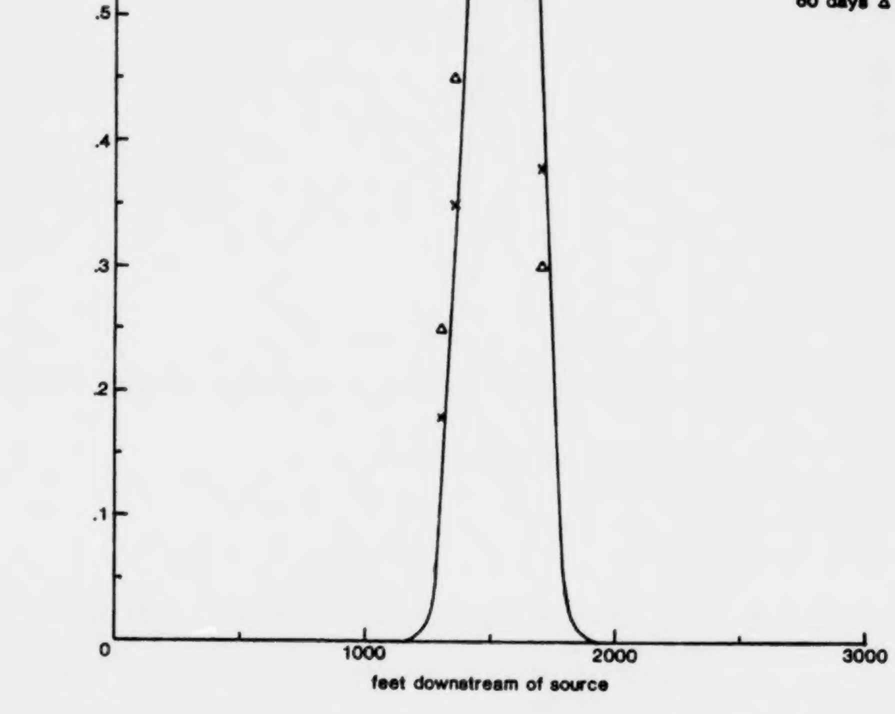

FIGURE 8-20 Slug duration sensitivity analysis (normalized).

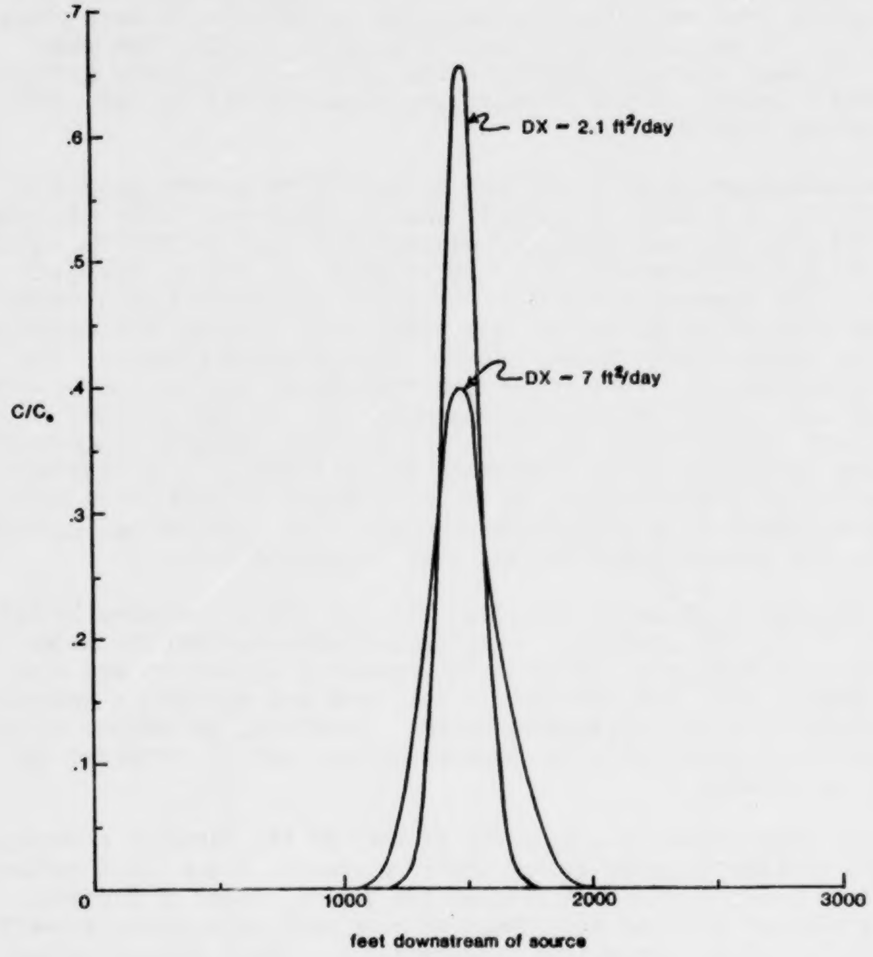

FIGURE 8-21 One-dimensional analytical model results at t = 1100 days for a slug duration of 90 days and seepage velocity = 1.4 feet/day.

GEOFLOW Application

GEOFLOW is composed of two parts, the flow model and the mass transport model. The flow model develops a velocity distribution which is used as input to the mass transport model. AQUIFEM was used to develop the basic flow model of Production Plated Plastics. Its calibrated input was to be transferred to GEOFLOW. A quadrilateral finite element grid was generated (Figure 8-22), and AQUIFEM's input interpolated to fit it. The piezometric head and velocities developed by GEOFLOW are very close to AQUIFEM's. It was a straightforward process to get the flow model running. The mass transport model, on the other hand, was very difficult to implement. Details of the problems are presented here to help other users avoid the same mistakes.

One of the advantages usually ascribed to the finite element method is its flexibility in fitting irregularly shaped boundaries. This advantage is minimized when the mass transport algorythm is used in GEOFLOW. Elements 10, 130, 191 and 199 were originally "triangular" to fit the assigned boundaries. The elements still had four nodes, but three were aligned, forming one side of the triangle. A concentration "source" was numerically generated at nodes located midway along a side of these elements. An oscillating contaminant front propagated from these "source" nodes, with every other node containing a zero concentration. GEOFLOW assigns an arbitrary base concentration (in this case zero) to negative concentrations, so the zeros replace negative components of the numerical oscillation. The concentration also continued to increase in the "source" node until it became large enough to abort the computer run. This problem was corrected by revising the element shape to that shown in Figure 8-22.

The area occupied by elements 215, 216, 217, and 218 was originally left as an interior no flow boundary. Once contaminants reached the nodes surrounding this area, the contamination tended to accumulate and stay there. Elements were then included in this area and assigned a hydraulic conductivity of .01 the surrounding value. Therefore, the effect on the flow system was substantially the same as before, and it corrected the concentration problem.

Contaminants also seemed to accumulate at some of the interior elements. Usually the problem occurred at odd shaped elements, those least rectangular, and at places where streamlines crossed the general trend of elements. The finite element grid was redesigned to have more rectangular elements that generally follow streamlines (Figure 8-23). These changes helped produce more reasonable plume movement.

The contamination seems to make an almost instantaneous translation from the source node to the surrounding nodes. From these nodes the contamination translates in a more reasonable fashion. The initial instantaneous movement has little effect on the long term solution, it can be minimized by having smaller elements near the source.

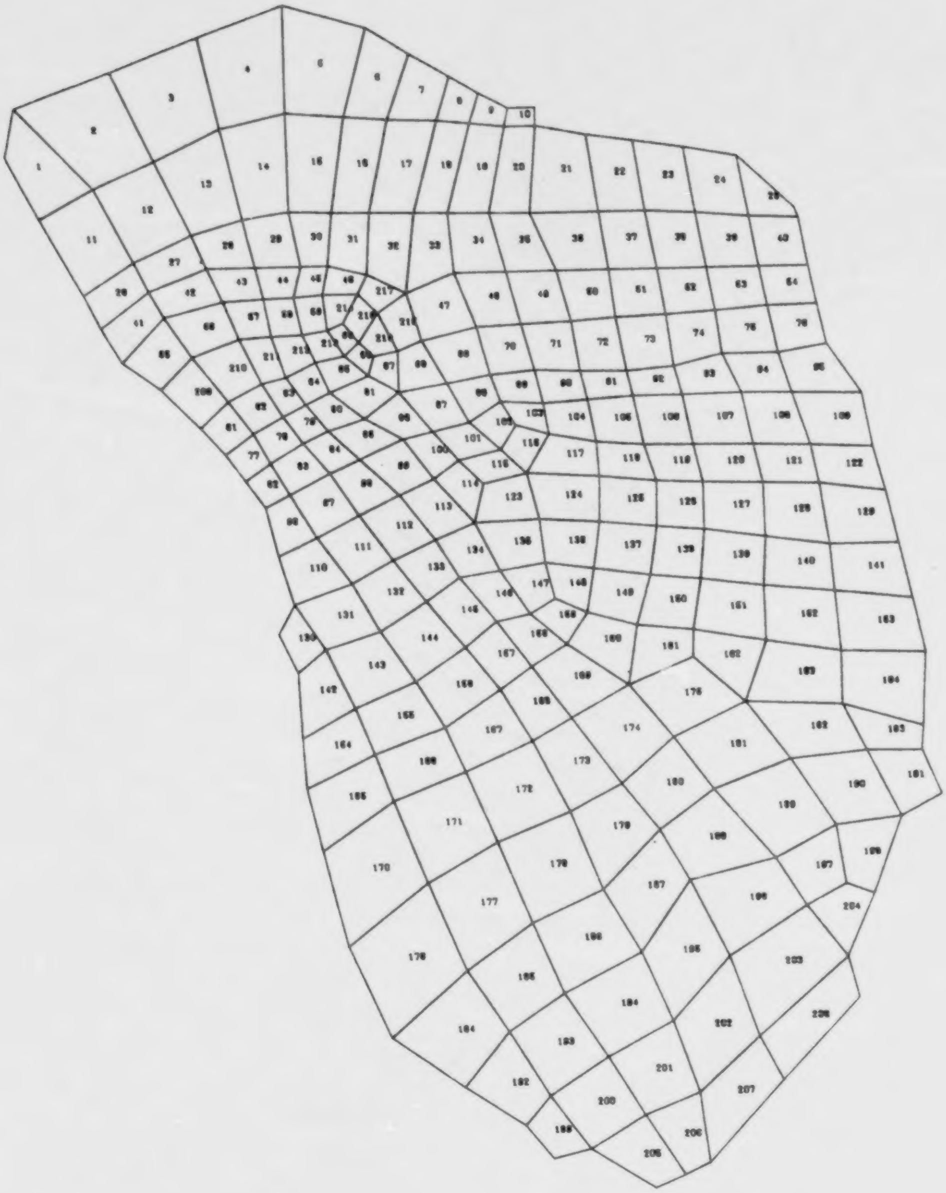

FIGURE 8-22 Regional finite element grid used with GEOFLOW.

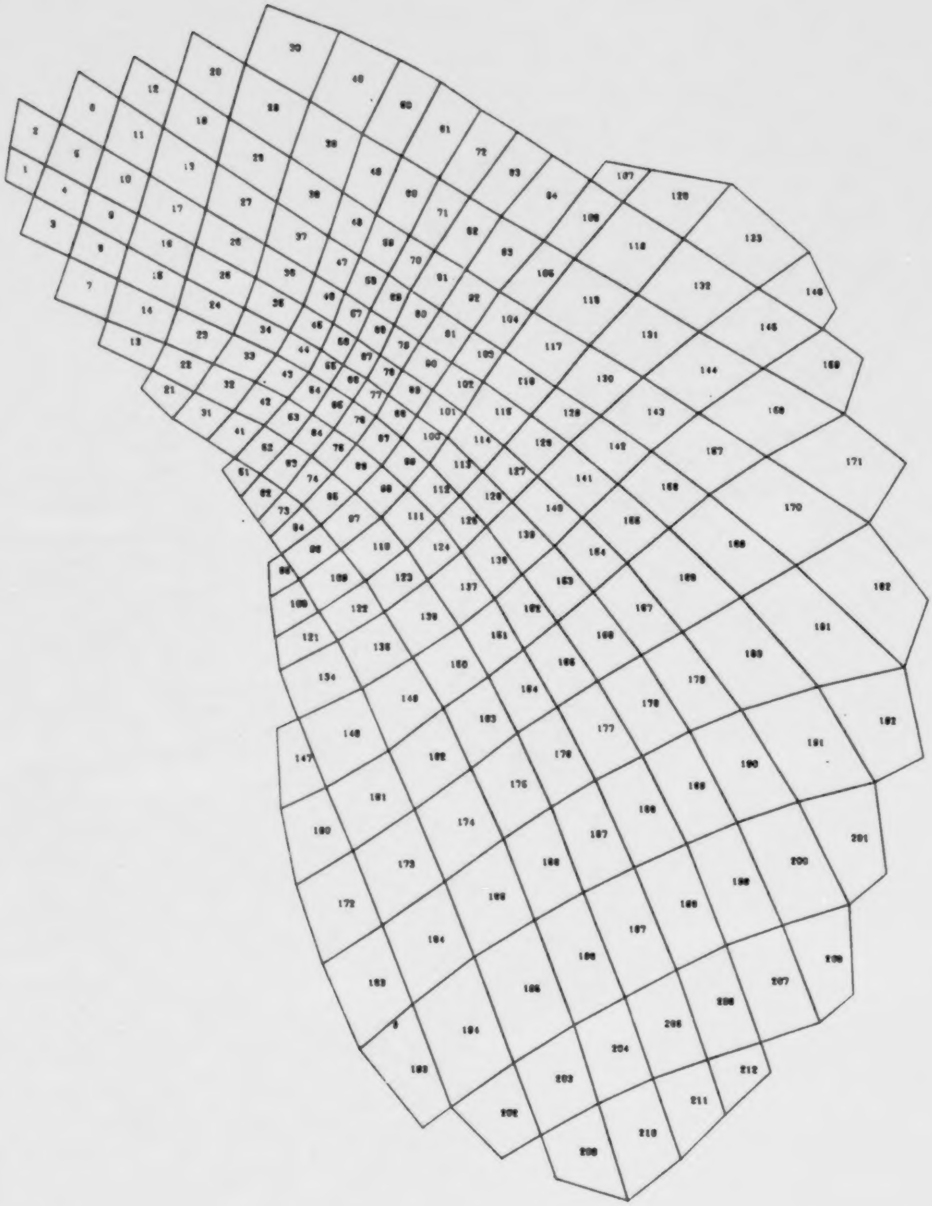

FIGURE 8-23 Redesigned regional finite element grid used with GEOFLOW.

There are several characteristics of finite element methods that can greatly affect the interpretation of mass transport model results. The effects can only be minimized and not eliminated. "Background noise" is inherent to the methodology. Background concentrations will not remain at zero, but will numerically be increased to some very small number. A numerically large source concentration will create a plume with concentrations large enough to be easily distinguishable from background noise. The concentration units are arbitrary and can be factored to any desired number. In the GEOFLOW runs a source concentration of 100,000 units was used.

Determination of the actual plume front is difficult. It is complicated by background noise, and more importantly by numerical dispersion along the front. Computer output must be carefully reviewed. By observing the concentration changes with time, a numerical oscillation can be identified which is associated with the front movement. This gives an indication of the predicted front, but it is still affected by numerical dispersion.

The effect of numerical dispersion is most pronounced in convection dominated problems; i.e., when the dispersivity is small, such as at Production Plated Plastics. Small dispersivities had also compounded earlier problems with artificial contaminant accumulations. Numerical dispersion is also affected by grid size and time step. As discussed earlier, the Peclet (Pe) and Courant (Co) numbers may be used as an indicator of when numerical dispersion may cause problems. When Pe and Co are both less than one, no numerical dispersion problems would be anticipated. This was the case when testing GEOFLOW in Chapter 5, and the numerical results corresponded almost exactly with analytical results.

Actual regional field situations can cause major problems in trying to meet the Pe criteria. At PPP, the estimated dispersivity is in the range of 1' to 5'. To maintain Pe at least near unity would require a grid size of the same order of magnitude as the dispersivity. For a regional scale study, this would strain present computer capabilities and certainly be cost prohibitive. Nevertheless, we still wanted to see if a finite element mass transport model could be applied to a regional problem and obtain reasonable results.

The finite element grid shown in Figure 8-23 was used for a regional mass transport simulation. It is a well designed grid, developed after much work in discovering the problems with the first grid. It conforms with all the above discussion, except that the Peclet number ranges into the hundreds. The number of elements and nodes used is relatively large (171 elements and 200 nodes), but computationally manageable. Steady state flow conditions coupled with mass transport cost in the range of tens of dollars per computer run. The same flow conditions developed with the AQUIFEM model were used. The source was assumed to originate from the discharge lagoons and last for 100 days, and the longitudinal dispersivity assigned as 5', with the transverse equal to 2'. Figures 8-24, 8-25 and 8-26 show the simulation plume concentrations at 1000, 3000 and 5000 days, respectively.

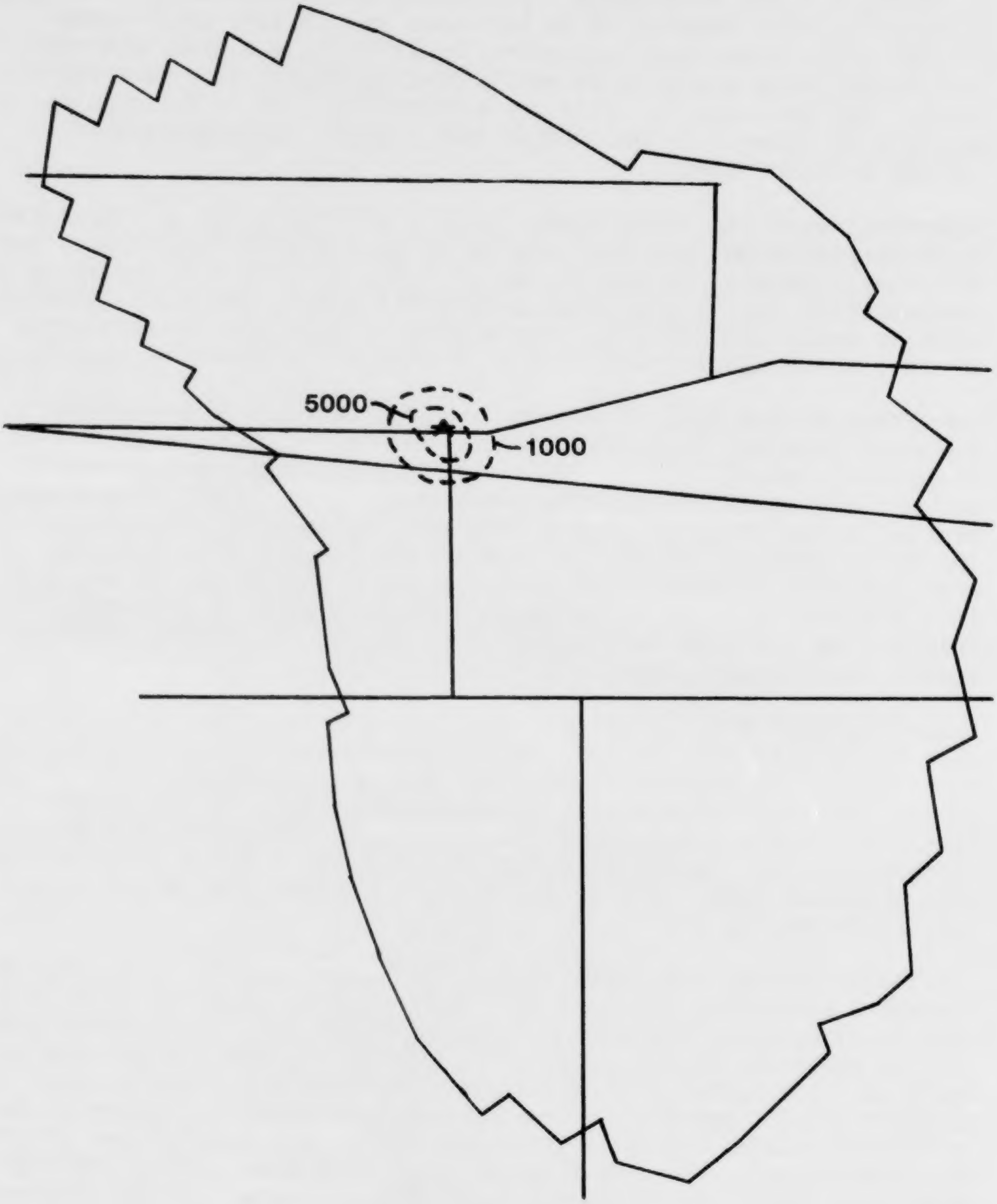

FIGURE 8-24 Simulated concentration contours at t = 1000 days, using the coarse grid for GEOFLOW with α_L = 5 feet and α_T = 2 feet. The concentrations are in arbitrary units. The source concentration was 100,000 units, the peak concentration here is 7750 units.

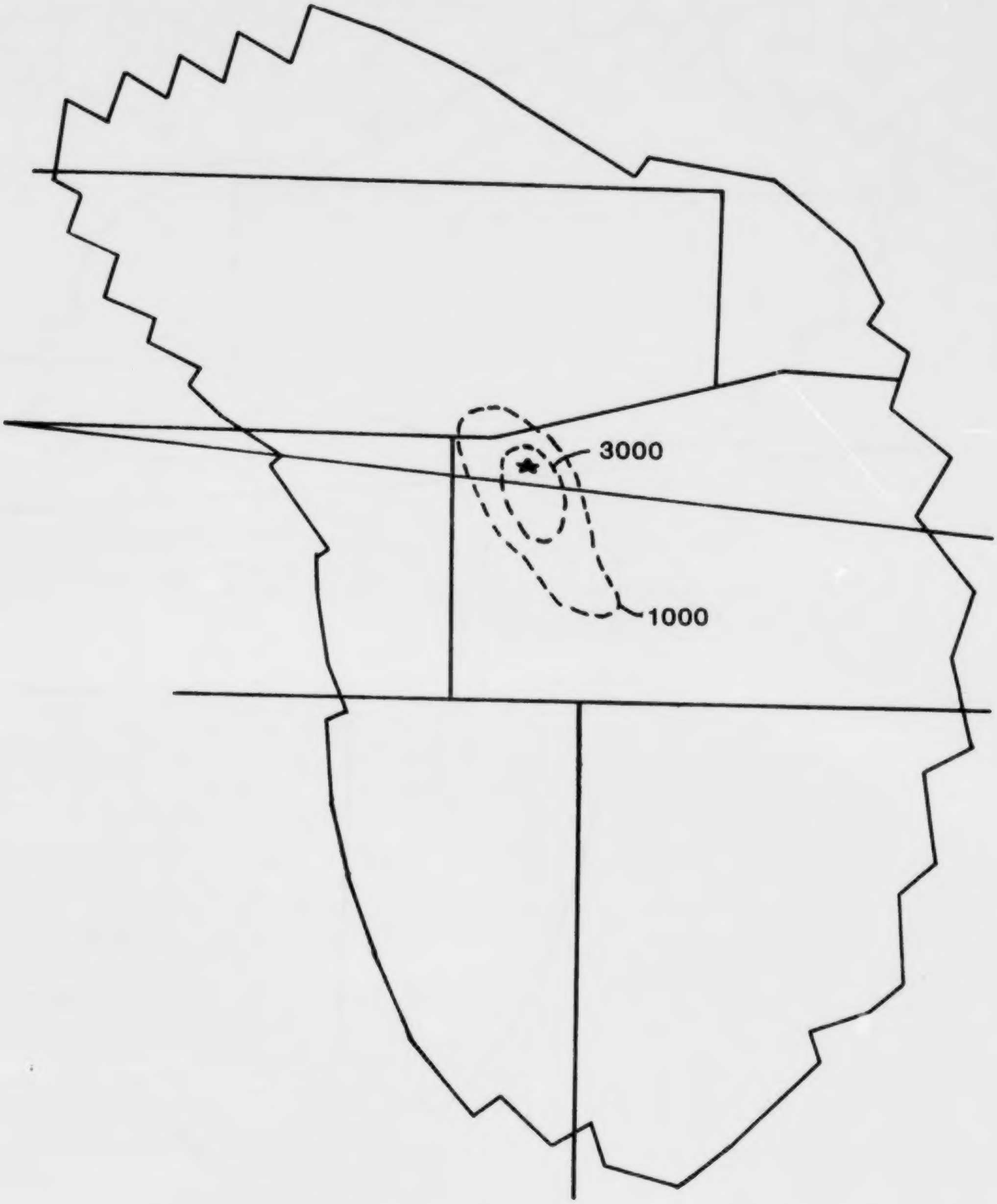

FIGURE 8-25 Simulated concentration contours at t = 3000 days, using the coarse grid. The peak concentration is 4500 units.

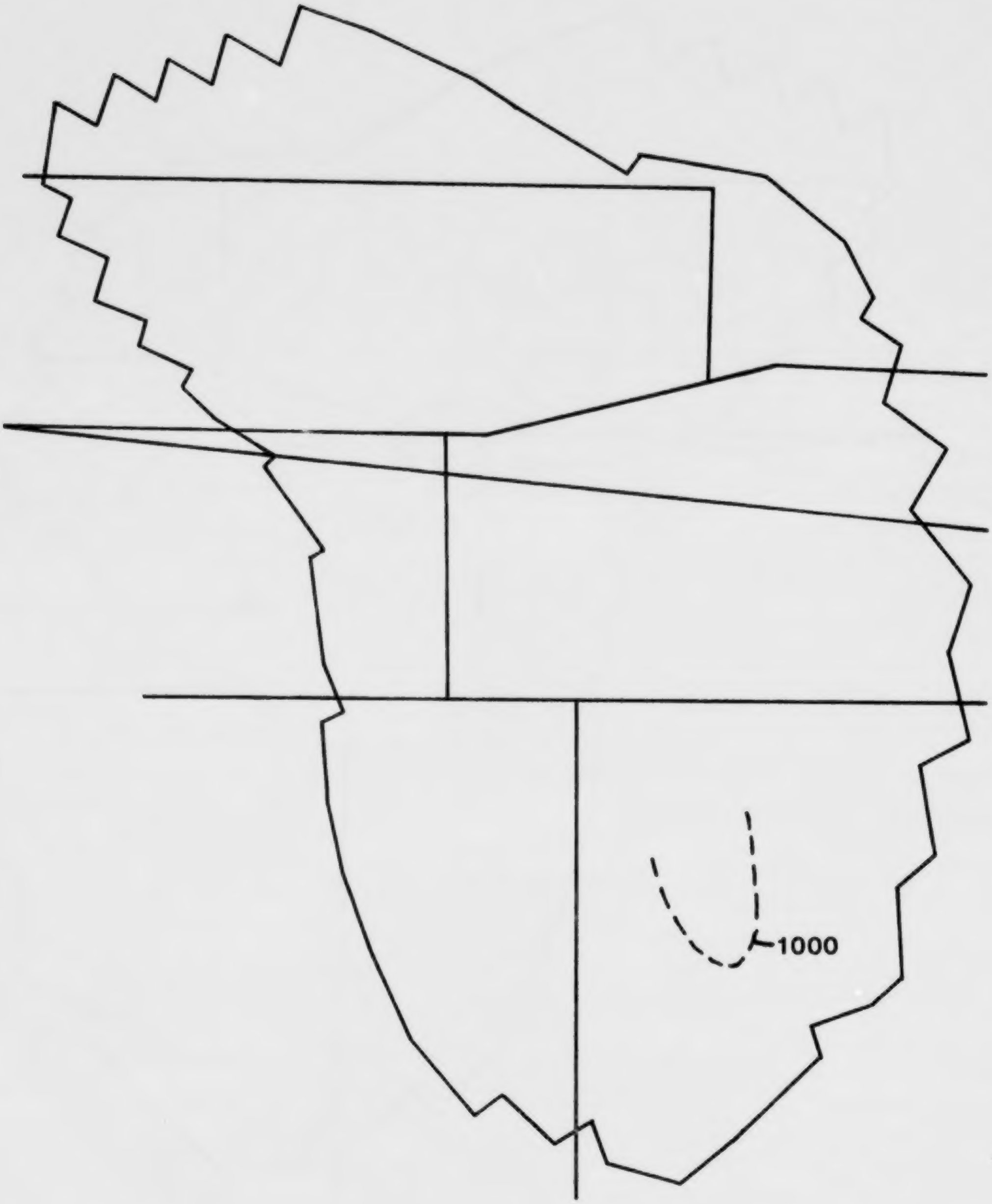

FIGURE 8-26 Simulated concentration contours at t = 5000 days. The plume could not be delineated because numerical dispersion in the coarse grid had erroneously dispersed the plume.

The plume translates in a reasonable manner, but the peak is much lower than would be expected from the analytical model results. After 5000 days the plume is so diffuse that it cannot be reliably delineated. Because the peaks were so low, it was suspected that numerical dispersion had greatly influenced the results. The only way to further improve the simulation was to develop a finer grid.

Wiggert, working with staff at D'Appolonia Consulting Engineers, greatly increased the number of elements. The refined grid contains 848 elements and 921 nodes and is presented in Figure 8-27. This is a very large grid, requiring a significant amount of computer core and time, and is very expensive to run. Peclet numbers still range between 30 and 120. Input into the model is the same as before. Output for 1000, 1800, 3000, 3600, and 5400 days are presented in Figures 8-28 to 8-32. The peaks are more in line with the expected values. The core of the plume is fairly concentrated with steep concentration gradients. It translates in a reasonable manner. A lot of the spreading appears to be numerical dispersion. Contamination seems to persist in areas after the plume passes through. This effect is most pronounced in Figure 8-32 after a long travel time. Its cause is unknown, but it appears to be numerically induced. At early times (Figure 8-28), the upstream fringe of the plume appears to be affected by the source. Again this seems to be a numerical effect.

The refined grid is a significant improvement over the earlier grid. However, numerical problems remain. Further grid refinement on a regional scale is limited by computer size and costs. Further refinement would be possible by using a more localized model. Artificial boundaries based on streamlines could define a strip or "stream tube" the plume would follow (Figure 8-33). The smaller scale would allow smaller elements. Great care and sensitivity analyses would be required in defining the boundary conditions. Time constraints did not allow further work in this direction and there is no guarantee that this approach would overcome the remaining numerical problems. Additional discussion of the GEOFLOW simulation may be found in Wiggert's report (Appendix D). Comparison of results with the other models is in a later section.

Wiggert and D'Appolonia personnel modelled a purge well system. Pumping began 3000 days subsequent to the injection of chromium at the PPP site. Twenty-two hours of computer time were required on the Prime 750 computer to simulate 5500 days of aquifer flow (it was necessary to predict both time variable flow and contaminant transport). Consequently, only one complete simulation has been completed, where a single 500 gpm purge well was located approximately at the leading edge of the plume. Unfortunately, the pumping rate was too extreme and resulted in dewatering the aquifer too rapidly, thereby failing to properly intercept and purge the plume.

When designing a purge well system, it is probably more important to assess the hydrodynamic response due to well placement than to attempt to model the subsequent contaminant migration. If the wells are properly located,

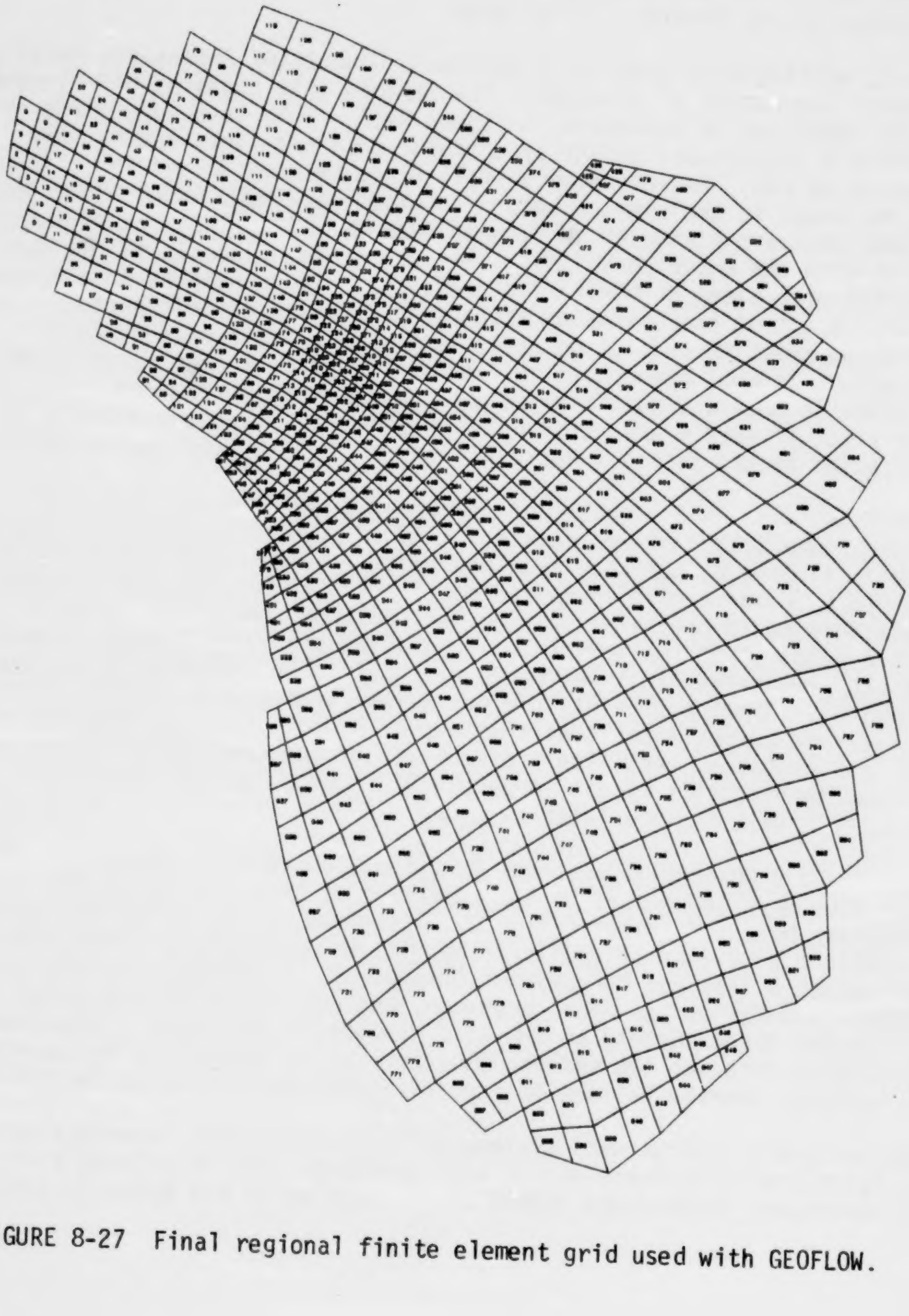

FIGURE 8-27 Final regional finite element grid used with GEOFLOW.

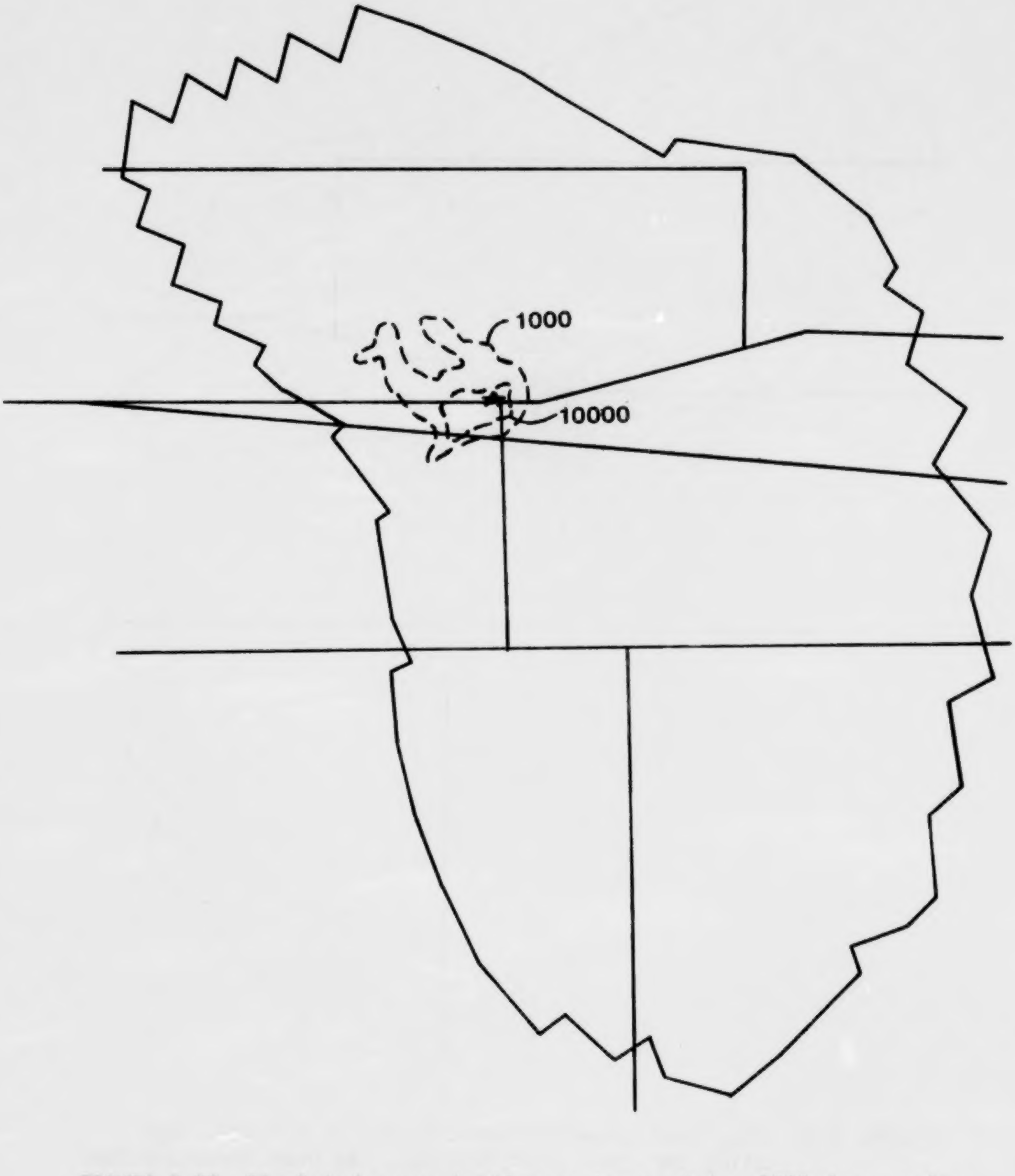

FIGURE 8-28 Simulated concentration contours at t = 1000 days, using the final grid for GEOFLOW with α_L = 5 feet and α_T = 2 feet. The concentrations are in arbitrary units. The source concentration was 100,000 units, the peak concentration is 37,700 units here.

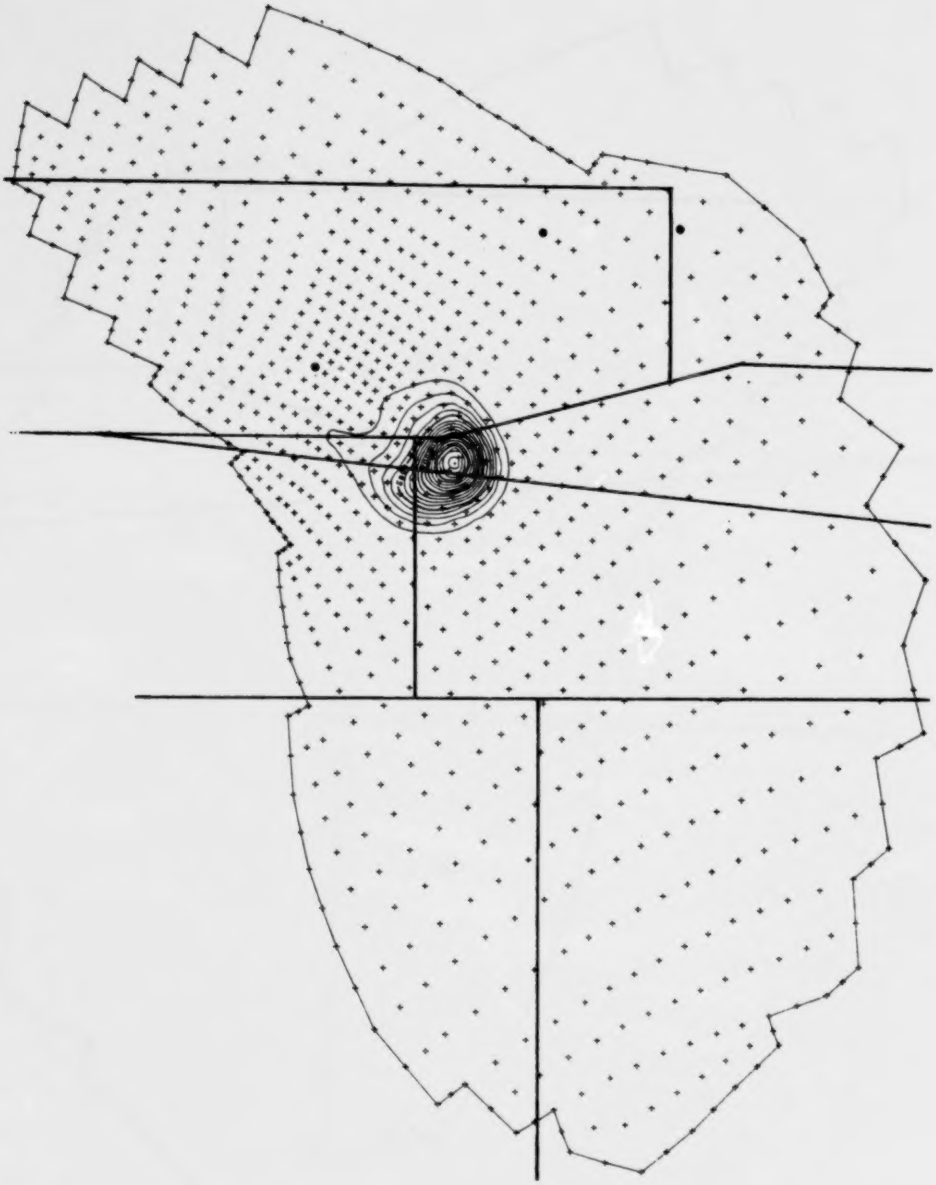

FIGURE 8-29 Simulated concentration contours at t = 1800 days using the final GEOFLOW grid. The peak concentration is 32,300 units.

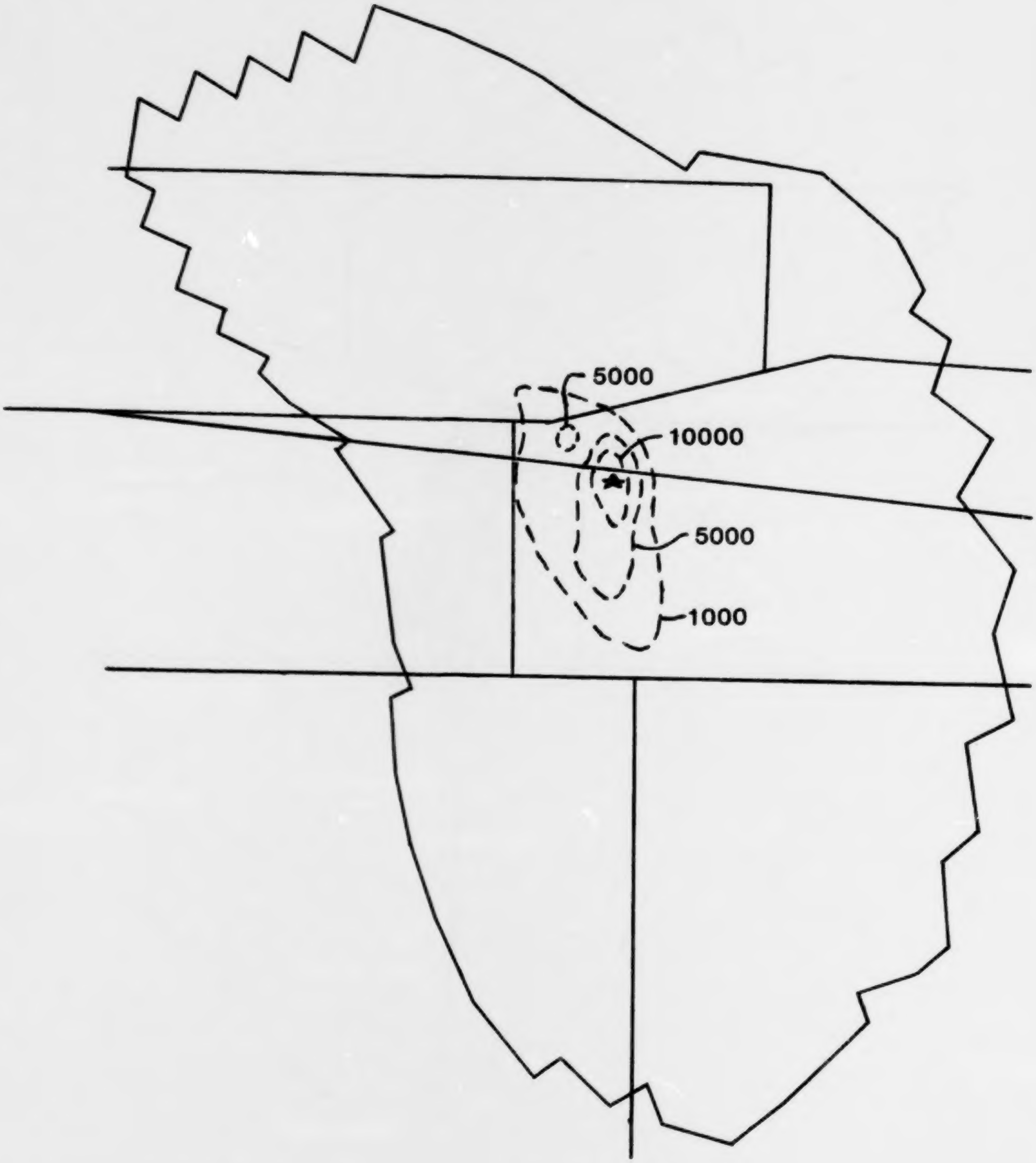
5000
10000
5000
1000

FIGURE 8-30 Simulated concentration contours at t = 3000 days using the final GEOFLOW grid. The peak concentration is 16,000 units.

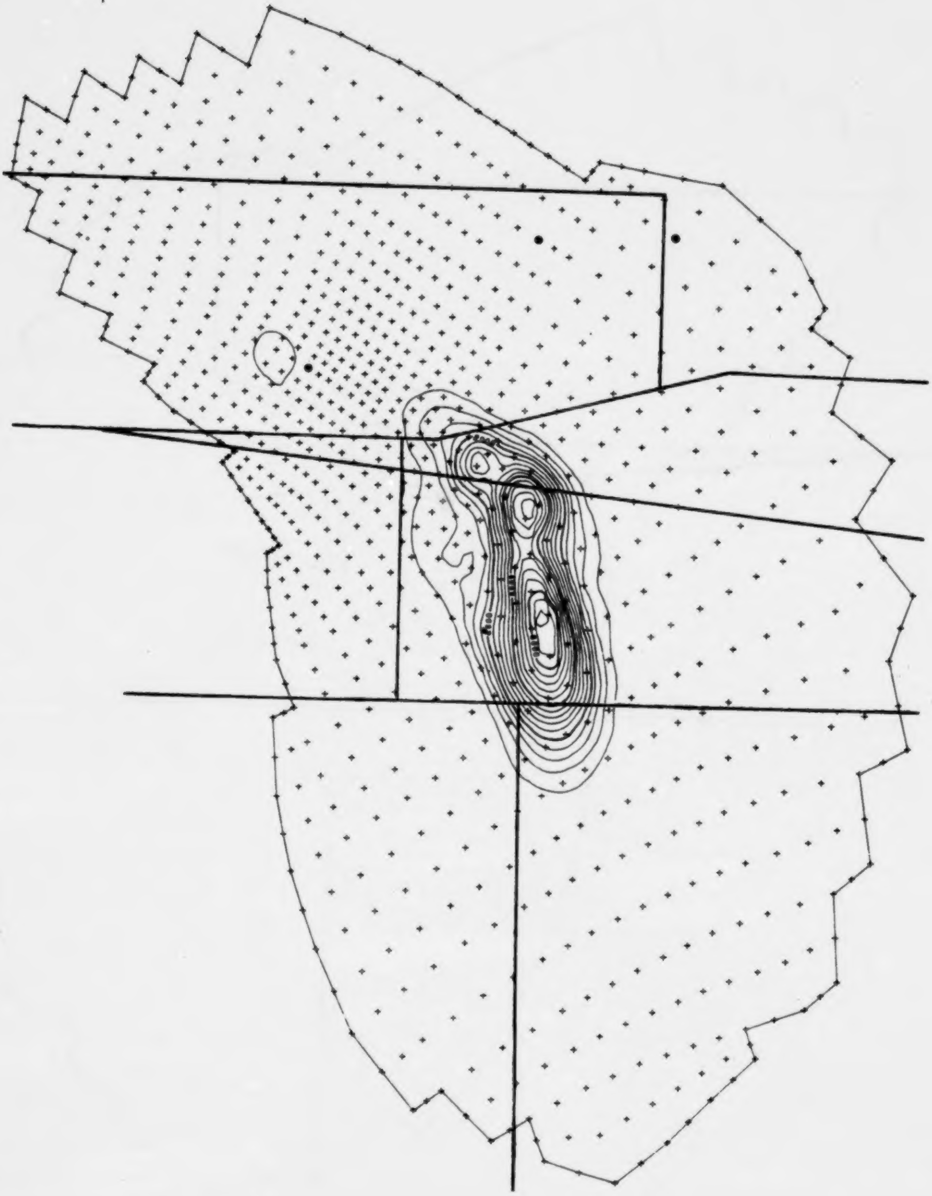

FIGURE 8-31 Simulated concentration contours at t = 3600 days using the final GEOFLOW grid. The peak concentration is 9,900 units.

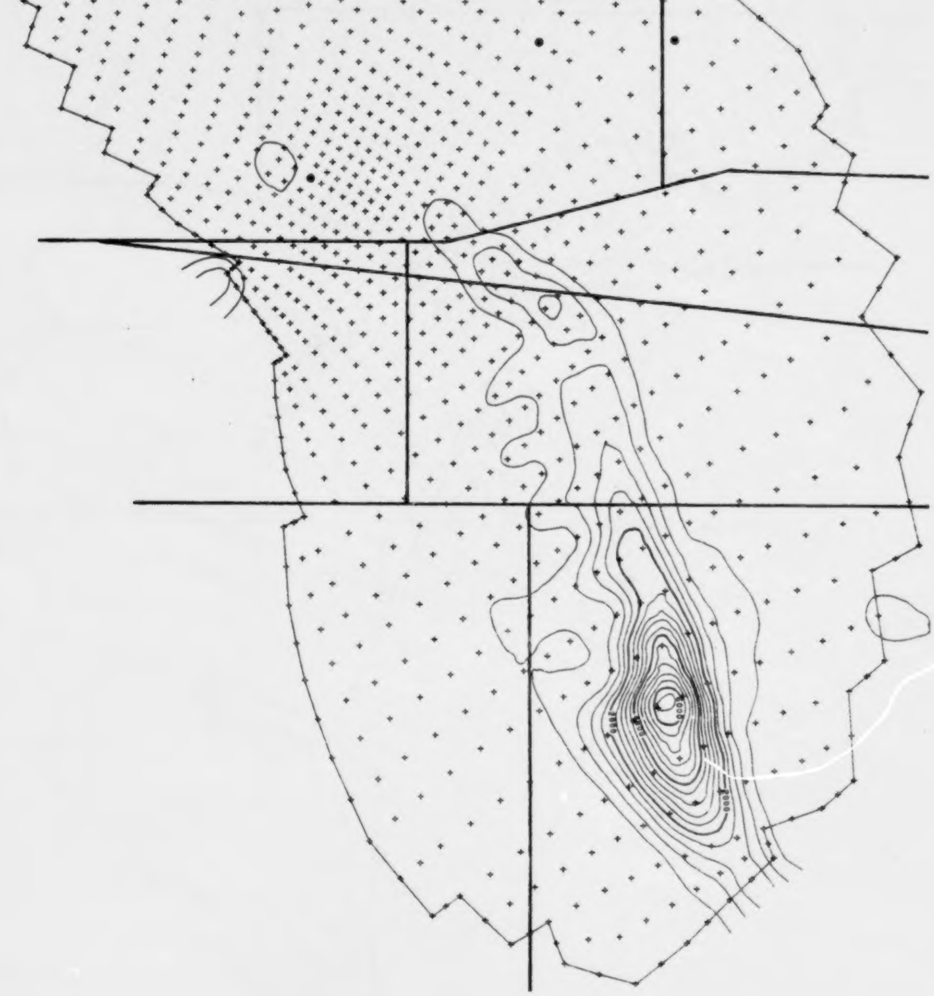

FIGURE 8-32 Simulated concentration contours at t = 5400 days using the final GEOFLOW grid. The peak concentration is 7500 units. Some numerical problems are still evident in the trailing edge of the plume.

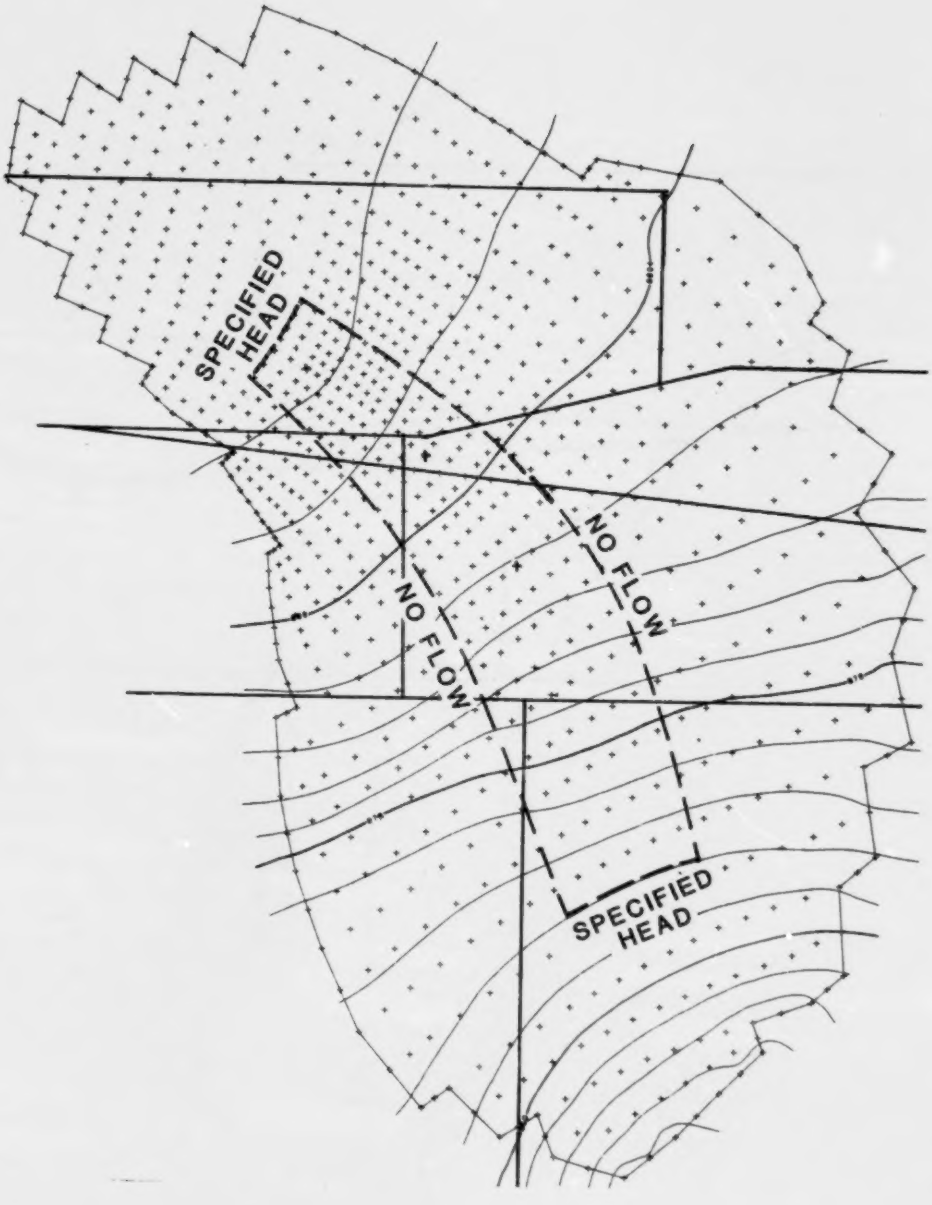
SPECIFIED HEAD
NO FLOW
NO FLOW
SPECIFIED HEAD

FIGURE 8-33 Concept of using artificial boundaries for an even more refined finite element grid. Placement of the boundaries would be critical and would require a sensitivity analysis.

the predicted flow patterns should reveal how successful the interception will be. In attempting to model the subsequent contaminant movement, the resulting numerical uncertainties can likely prevent an accurate estimation of the residual contaminants present in the system.

Two possibly viable purge well systems have been selected and the resulting hydrodynamic solutions are shown in Figures 8-34 and 8-35. In Figure 8-34, two purge wells (F,G) are each pumping 150 gpm and in Figure 8-35, an additional third well (H) is pumping 100 gpm. The flow patterns indicate that with either of these two arrangements, a significant portion of the plume will be intercepted.

USGS Mass Transport Model Application

The USGS Mass Transport Model was also applied at Production Plated Plastics. Wright made this simulation and his report is contained in Appendix C. Runs were made using both a small and large grid. The small grid covered essentially only the areas where the chromium data were available and consisted of 125 feet long by 125 feet wide spacing between nodes over the region depicted in Figure 8-36. The larger grid covered most of the known groundwater flow system and consisted of nodes on 500 feet by 250 feet spacing as in Figure 8-37. Input for the flow model was developed from the AQUIFEM simulation. Water table elevations from AQUIFEM are used as boundary conditions for these simulations.

Water table contours computed from the USGS model compared very well with the AQUIFEM results. A variety of runs were made. Results for the larger grid do not have sufficient resolution to compare against field observations, particularly at the smallest dispersivities. On the other hand, the small grid did not extend far enough to predict future plume movement. The source for these simulations is assumed to be a spot near the lagoons where puddles with high levels of chromium were observed during a DNR inspection. Figure 8-38 contains the predictions of the plume migration predicted with the small grid. Included is the trajectory extrapolated from the computed results and peak values at selected times. Also included is a concentration profile at a particular time when the slug is in the vicinity of the observation wells. Concentrations are relative to an arbitrary source value of 1000 and do not represent an absolute measure of concentration. Note the USGS model does not necessarily predict continuously decreasing peak concentrations with time. This is due to the fact that the concentration peak can lie in between nodes and be averaged out over several, whereas at a later point in time, it can be more or less aligned with a single node. Figure 8-39 is a similar plot with the large grid simulation results.

Figure 8-40 is an attempt to predict the present location of the slug. Slightly higher dispersivities (lateral = 5 feet, transverse = 1.5 feet) were used and are consistent with what was used in the other models. Esti-

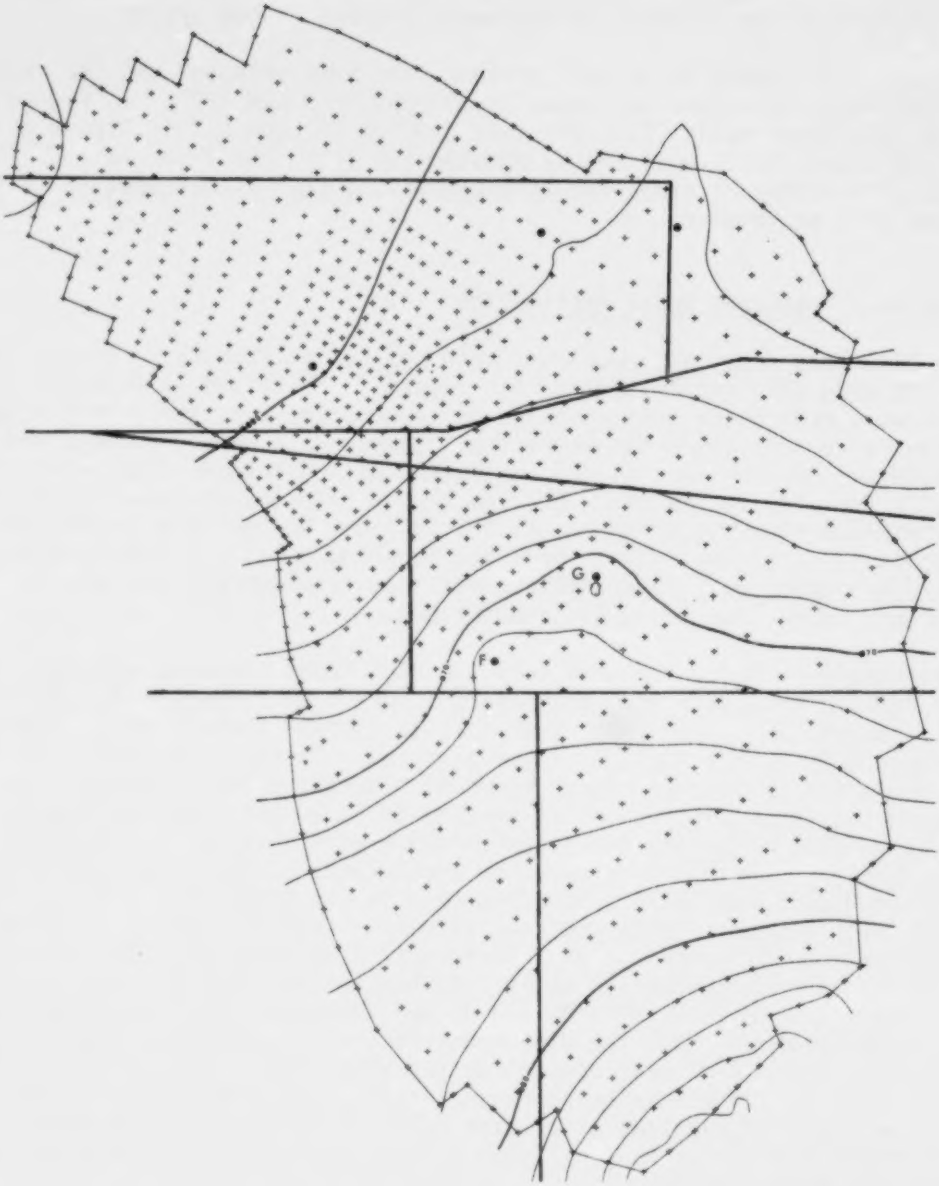

FIGURE 8-34 Predicted piezometric contours with two purge wells, each pumping 150 gpm, at F and G.

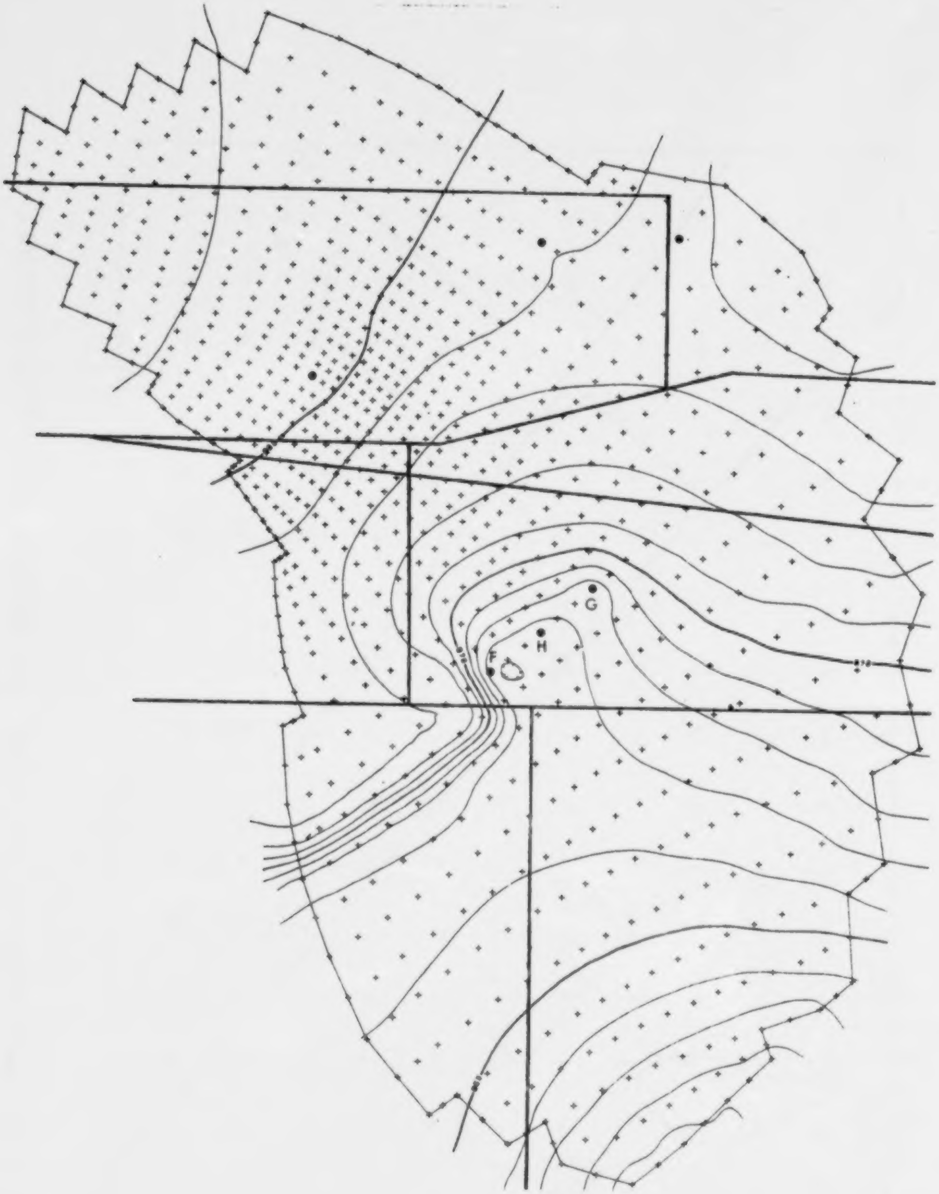

FIGURE 8-35 Predicted piezometric contours with three purge wells, each pumping 100 gpm, at F, G and H.

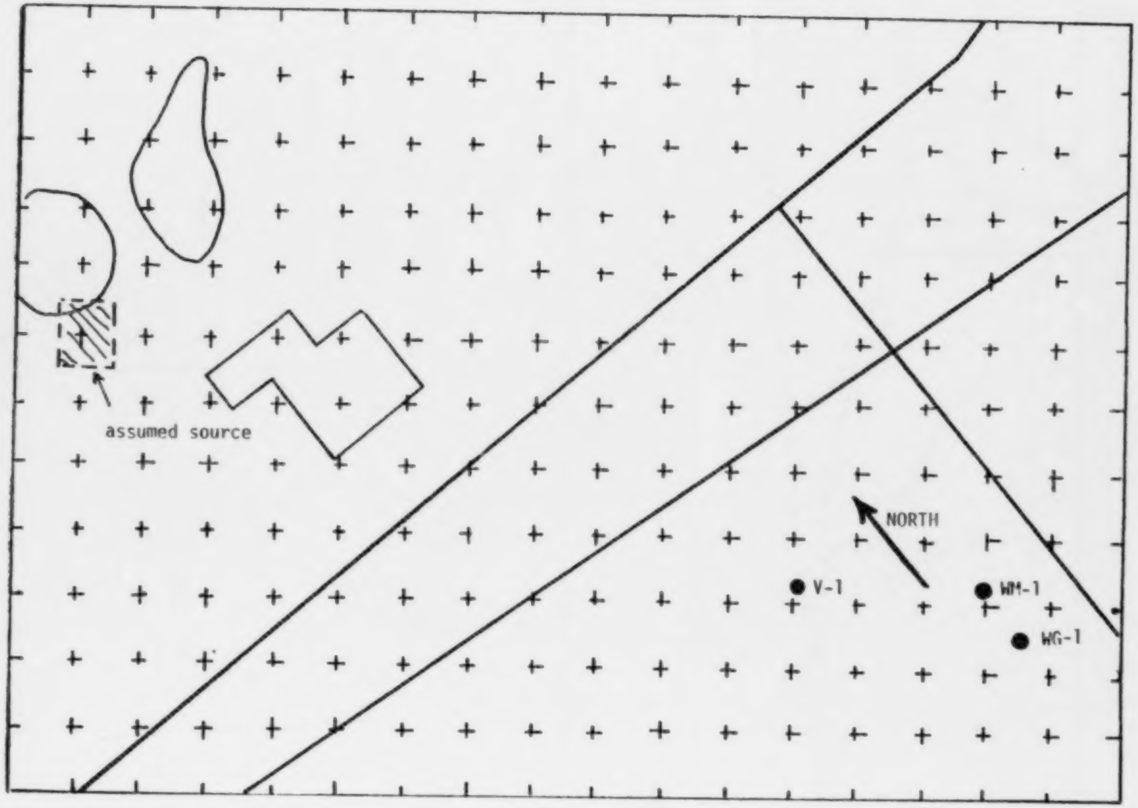
assumed source
NORTH
V-1
WM-1
WG-1

FIGURE 8-36 Small numerical simulation grid at Production Plated Plastics, using USGS Mass Transport Model.

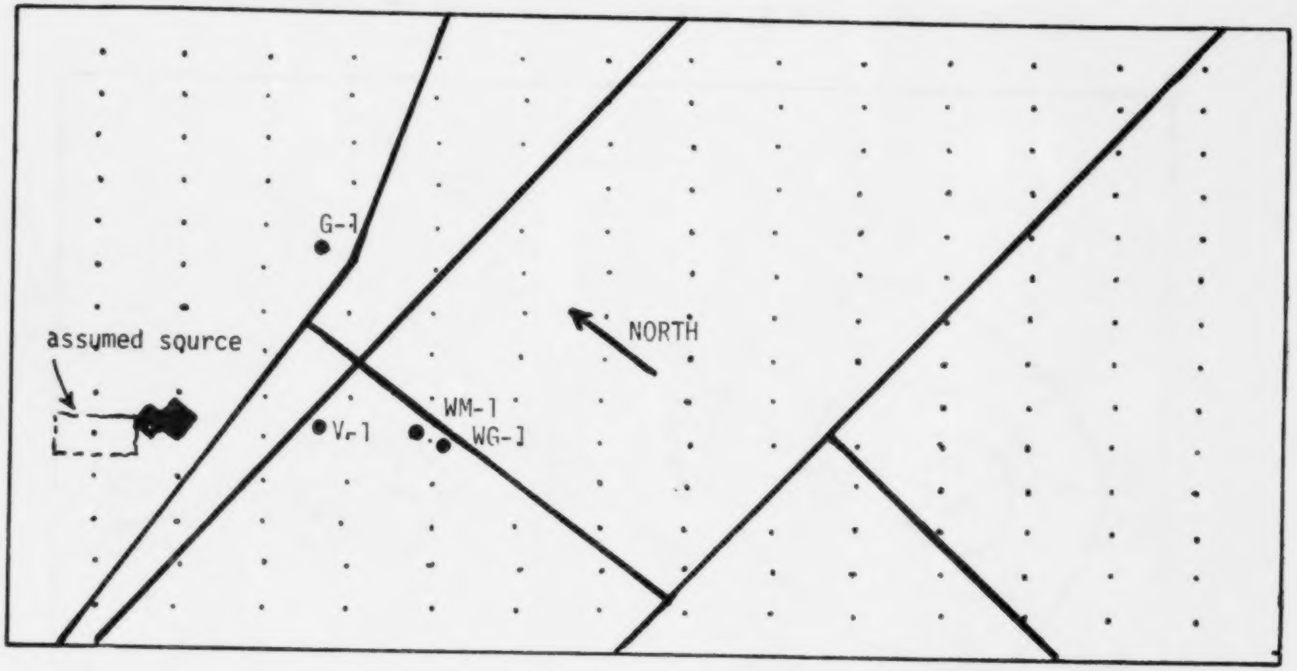
G-1
assumed source
NORTH
WM-1
V-1
WG-1

FIGURE 8-37 Large numerical simulation grid at Production Plated Plastics, using the USGS Mass Transport Model.

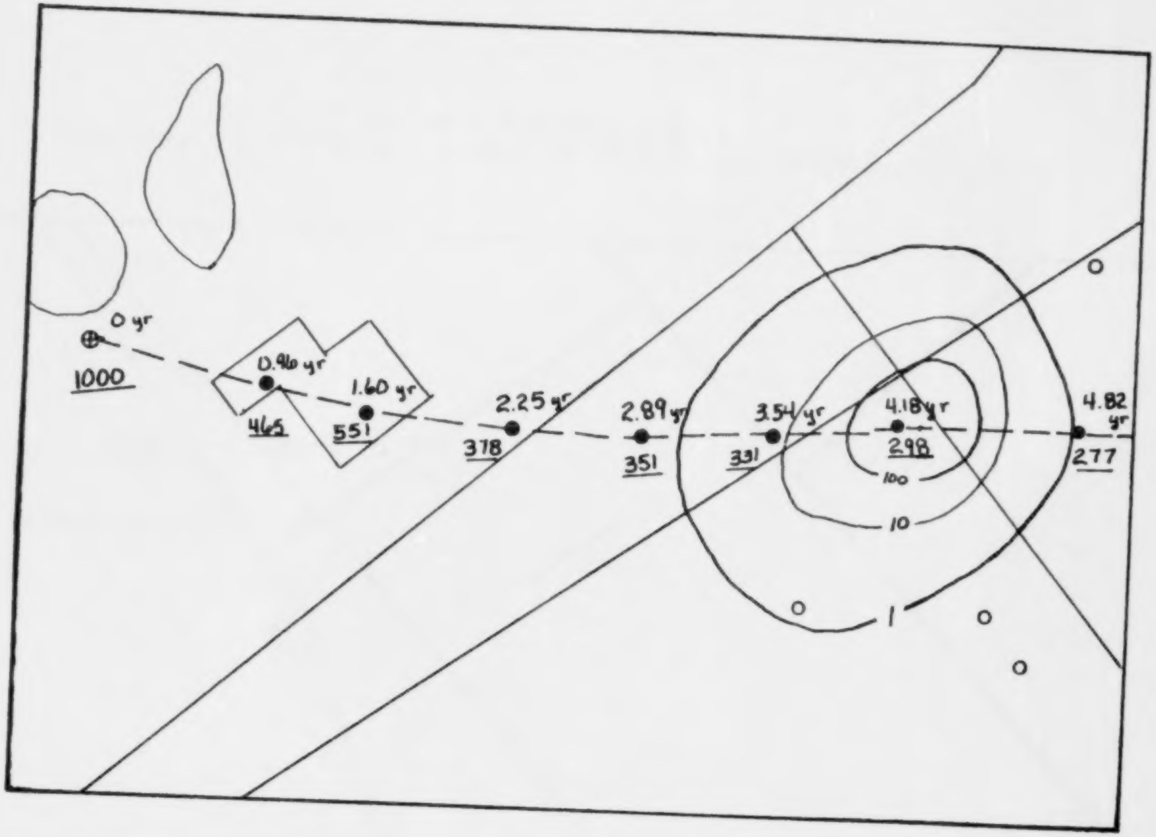
0 yr
1000
0.96 yr
465
1.60 yr
551
2.25 yr
378
2.89 yr
351
3.54 yr
331
4.18 yr
298
4.82 yr
277
100
10
1

FIGURE 8-38 Computed plume path and profile at 4.18 years from small grid (arbitrary concentration units), $\alpha_L = \alpha_T = 1$ foot.

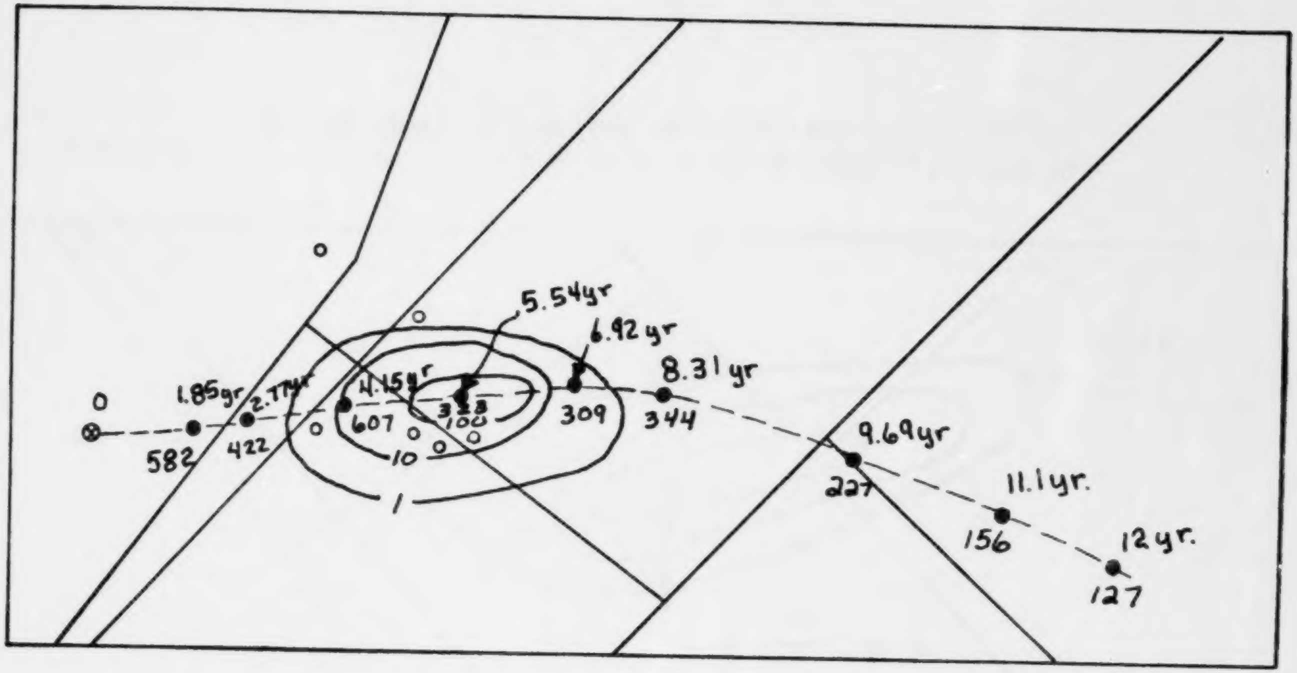
1.85yr
582
2.77yr
422
4.15yr
607
5.54yr
328
100
10
1
6.92yr
309
8.31yr
344
9.69yr
227
11.1yr.
156
12yr.
127

FIGURE 8-39 Computed plume path and profile at 5.54 years from large grid (arbitrary concentration units), $\alpha_L = \alpha_T = 1$ foot.

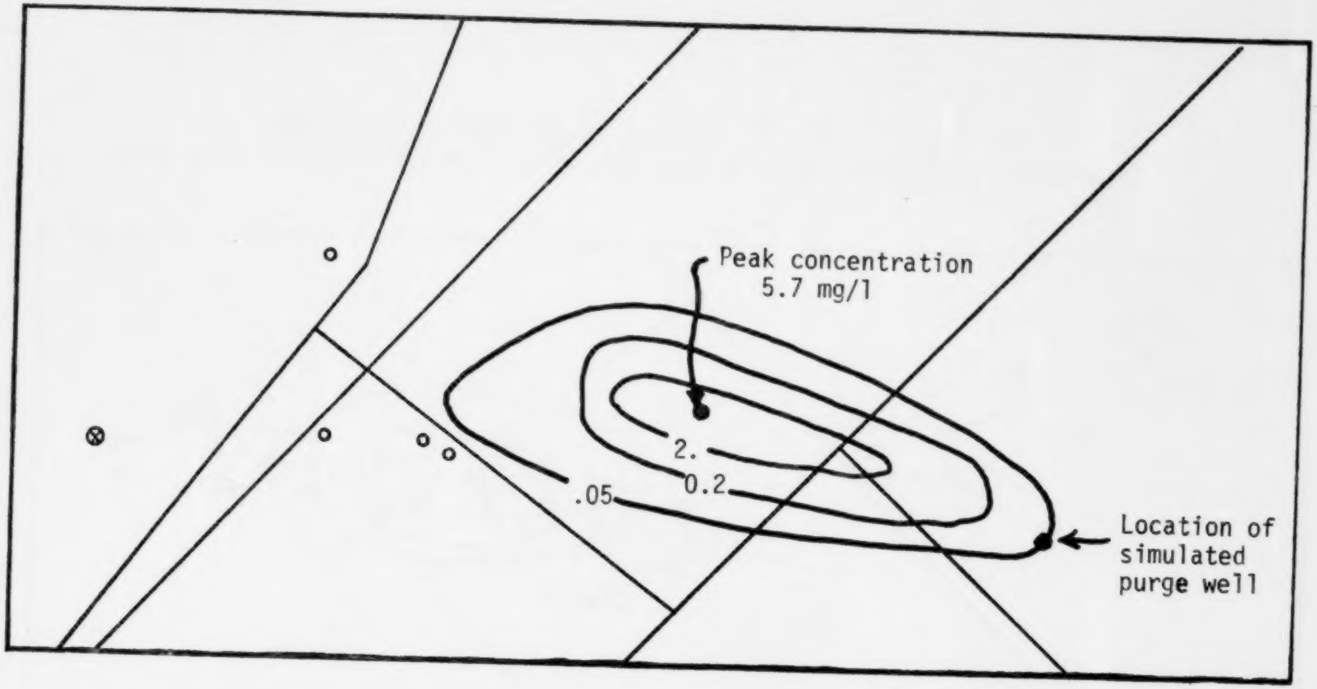
Peak concentration
5.7 mg/l
2.
0.2
.05
Location of
simulated
purge well

FIGURE 8-40 Estimated chromium plume location (March 1982) using USGS Mass Transport Model, α_L = 5 feet, α_T = 1.5 feet.

mates of the actual concentrations were made by relating the arbitrary concentration units to measured concentrations when the simulated plume passed through the area with observation wells.

Graphical results are not presented for the two pumping runs. For the two pumping rates of 250 gpm and 1000 gpm, the purge well, as located in Figure 8-40, would successfully capture all of the contaminant for the dispersivities used. Obviously before any attempts are made to install an actual purge well system, further monitoring should be done to determine the extent of contamination, and aquifer tests performed to provide better estimates of aquifer parameters.

Comparison of Results

Additional runs were made with the analytical models for more direct comparisons with the numerical models. Table 8-3 compares the relative peak concentrations from several simulations. The analytical runs with velocities of 1.25 and 1.0 ft/day and 100 day slug duration are closest to the conditions simulated in GEOFLOW. Concentrations from the coarse grid are much lower than the analytical results. This is because of the excessive numerical dispersion present in the coarse grid. The finer grid was more consistent with analytical results. GEOFLOW results are slightly smaller, but this is expected. GEOFLOW incorporates the velocity variations, accretion, and changes in flow direction expected in the real groundwater system. These factors would tend to increase the dispersion and produce lower peak concentrations relative to the analytical model. Numerical dispersion is still evident around the edges of the plume, but the peak appears to be preserved pretty well. It is difficult to differentiate between dispersion induced by "natural" or numerical factors. For example, the peak concentration of the finer grid at 5000 days is considerably smaller than the analytical value. It is unknown whether this is a cumulative effect from "natural" dispersion or largely a result of numerical dispersion, or a combination of both. Only further work with an even more refined grid can answer this question. In any case, a reasonable range has been established. *We would not expect concentrations greater than indicated by the analytical model and GEOFLOW would likely represent the lower end of probable peak concentrations.*

The USGS Mass Transport Model is more difficult to compare with the analytical model. Its source covers an entire element. All the water within that element is assigned a relative concentration of 1.0 initially. Concentrations reported at nodes represent an average based on the particles present in the element at each time step. When the peak is located between nodes, it is averaged between the nodes. Therefore, the peak concentration reported at the nodes can go up or down each time step, depending on the location of the actual peak relative to the nodes. This is demonstrated in Figure 8-41 where the peak nodal value is plotted for each time step. A curve was fit to the greatest peaks in an attempt to estimate the actual

TABLE 8-3

Comparison of peak relative concentrations (C/C_0) from mass transport models, $\alpha_L = 5$ feet, $\alpha_T \approx 1.5$ feet.

	GEOFLOW		ANALYTICAL							USGS
Time (days)	coarse grid	finer grid	V (ft/day) = 1.4 SLUG (days) = 100	1.25 100	1.00 100	1.25 200	1.00 200	1.25 500	1.00 500	
1000	.08	.38	.44	.42	.39	.74	.70	.97	.99	—
3000	.045	.16	.20	.19	.19	.37	.36	.70	.72	.69
5000	.013	.075	.13	.12	.12	.24	.24	.51	.53	.36

TABLE 8-4

Ratio of peak concentrations ($\frac{C/C_0 \text{ @ } t = 3000 \text{ days}}{C/C_0 \text{ @ } t = 1500 \text{ days}} \times 100\%$).

GEOFLOW	ANALYTICAL			USGS
finer grid	V (ft/day) = 1.25 SLUG (days) = 100	1.25 200	1.25 500	—
50%	58%	62%	77%	64%

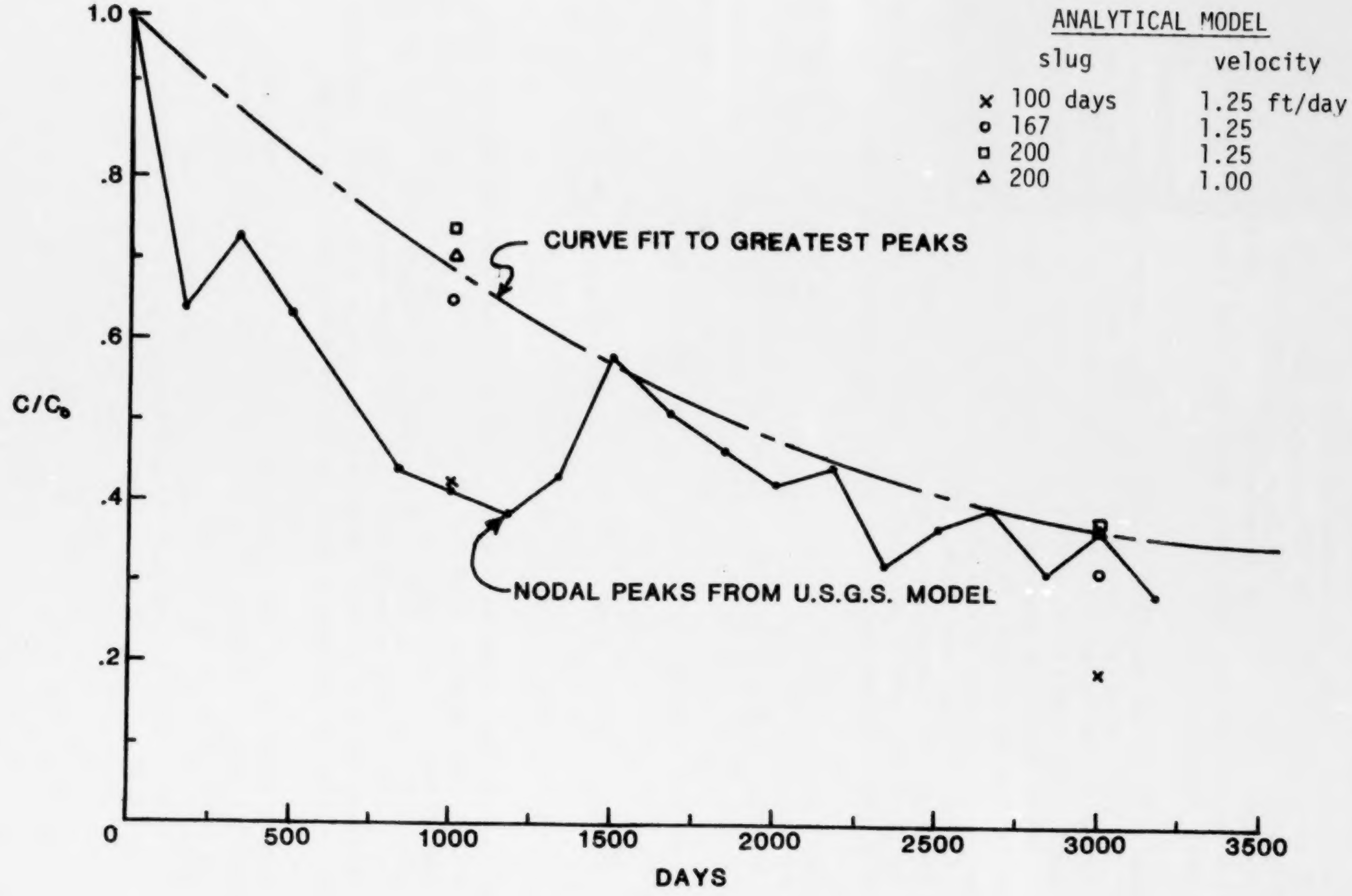

FIGURE 8-41 Peak nodal values from USGS Mass Transport Model compared with analytical results.

peaks calculated by the model at each time. Values from this curve can then be compared with the analytical model. But there is still a problem in developing a reasonable comparison with the analytical model. An attempt to reproduce the same contaminated source area and mass loading by using a slug duration of 500 days yields analytical peaks much greater than the USGS model. A slug duration of 200 days yields almost identical relative concentrations (see Table 8-3), but used significantly less total mass loading.

Apparently it is not possible to make a direct comparison between the analytical mass transport models and the USGS model at relatively short times and with the large grid spacing (250 feet x 500 feet) used in the USGS model. The analytical models give the exact concentration at a point, whereas there is always some averaging within an element in the USGS model. To compare the two models, it would probably be necessary to somehow have the analytical concentrations averaged over an area equivalent to the element area. At relatively long times, after dispersion has significantly flattened the peak and spread the plume over many elements, it is expected that the peak concentrations from the models would become more comparable. With very low dispersivities this could take a very long time.

Analytical model results are plotted on maps for a more direct comparison with the numerical models. In Figure 8-42 an approximate streamline is drawn directly from the lagoons. Along this streamline the location and peak concentrations are shown at different times for average velocities of 1.4 and 1.25 ft/day. Some concentration contours are drawn in for the estimated present plume location (t = 3000 days). As discussed earlier, the analytical plume is much smaller than the one generated by GEOFLOW (see Figure 8-30). The peak from GEOFLOW lags behind the analytical with v = 1.25 ft/day at t = 3000 days; but is approximately the same as the analytical with v = 1.4 ft/day at t = 5000 days. This demonstrates the velocity variation incorporated in GEOFLOW.

In Figure 8-43 an approximate streamline is drawn from the source area used in the USGS model. Some concentration contours are drawn in for the estimated present plume location. The plume shape and location compares quite favorably with the USGS model plume (see Figure 8-40). The analytical plume is a little less elongated. The USGS model results may be a little more disperse because of the large initial source area, nodal averaging of concentrations, or perhaps a small amount of numerical dispersion.

The general behavior of the plumes in all three models is reasonably consistent. They propagate well, except for the numerical dispersion problems still present in GEOFLOW. They tend to indicate similar peak concentration reductions. We would expect that the present peak concentration is about 60% of what it was when it was monitored in the domestic wells (see Table 8-4).

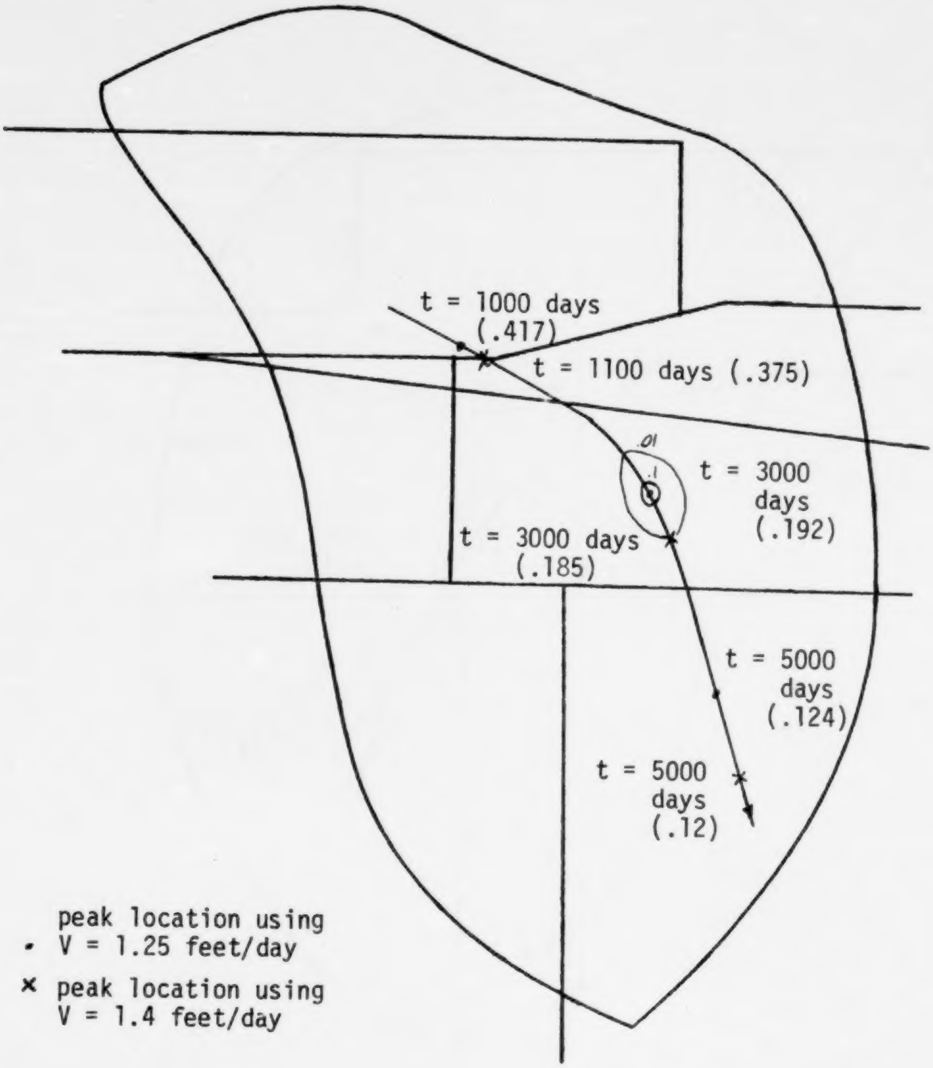
t = 1000 days
(.417)
t = 1100 days (.375)
.01
.1
t = 3000 days (.192)
t = 3000 days (.185)
t = 5000 days (.124)
t = 5000 days (.12)
peak location using
• V = 1.25 feet/day
× peak location using
V = 1.4 feet/day

FIGURE 8-42 Analytical mass transport peaks along a streamline (α_L = 5 feet, α_T = 1.5 feet). The peak relative concentration (C/C_0) is shown in parentheses. This streamline is the same one used in the GEOFLOW analysis.

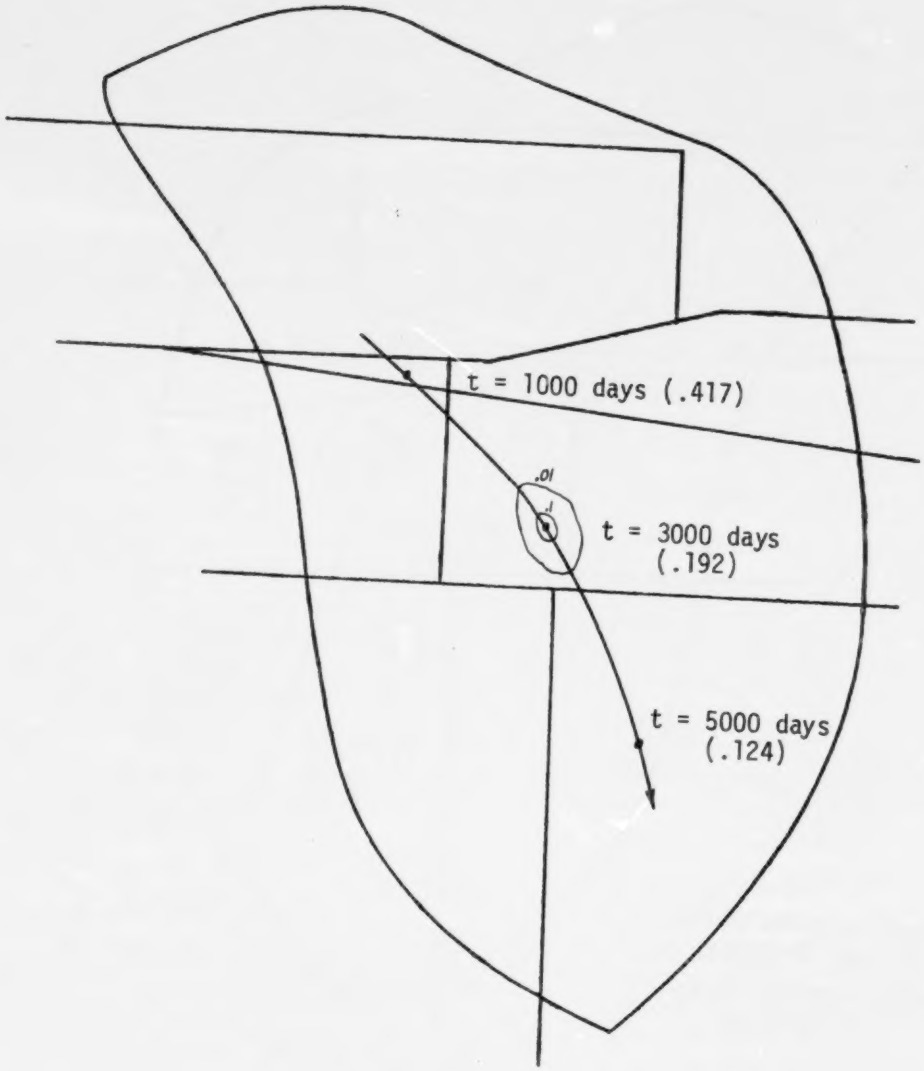
t = 1000 days (.417)
.01
.1
t = 3000 days (.192)
t = 5000 days (.124)

FIGURE 8-43 Analytical mass transport peaks along a streamline (α_L = 5 feet, α_T = 1.5 feet, and V = 1.25 feet/day). The peak relative concentration (C/C_0) is shown in parentheses. This streamline is the same one used in the USGS Mass Transport analysis.

Uses of the Models

The completed models form a powerful management tool. They represented the current interpretation of all the data available at the time of their completion. All the known complexities of the hydrogeologic system were incorporated into models capable of dynamic simulation.

The first management problem was determination of the present plume location. The USGS model results (Figure 8-40) probably represented the best estimate of the principal plume location, although it was not significantly different from the analytical model. The streamline followed passes directly through the contaminated domestic wells and originates at a probable spill location. It should also be recognized that there are other likely contamination sources, especially the lagoons. These additional plumes would follow more northerly streamlines, such as the one used in GEOFLOW. The plumes can be further projected into the future, but the associated uncertainty increases dramatically. Further projections are useful to estimate the plume behavior if no remedial action is taken. If these projections are important, then additional field work must be undertaken to determine the hydrogeology along the plume's projected path. While the models incorporate the best available data, away from the area covered by the hydrogeologic study the data consists of rough extrapolations from well logs and surface topography.

The model can be coordinated with additional field work. Projections of plume location served as a guide for the installation of new wells. Data gathered from the new wells can be incorporated into the model and used to help direct additional field work. Similarly, the model can help design a purge well system. Pumping wells can be simulated based on the available data. As more data are obtained and incorporated into the model, the more accurate and reliable the model results become. Preliminary purge well systems were simulated, as discussed briefly in an earlier section.

Coordination with Field Work

Additional field work provided an opportunity to evaluate the projections and directly coordinate the model with field work. The field work was authorized and initiated before model results could be presented to Keck Consulting Services, the consultants for PPP. So the first new wells were installed without guidance from the modeling effort. The new wells (Figure 8-44) revealed complications that could not have been predicted and provided valuable new data.

Apparently a trough does not extend to the east. The well logs indicate that east of the main trough the aquifer bottom rises to about 860 and drops back to about 850. The soils encountered are also siltier than those earlier encountered. These discoveries necessitated revision of the aquifer bottom elevations and inclusion of a low permeability zone (Figure 8-45).

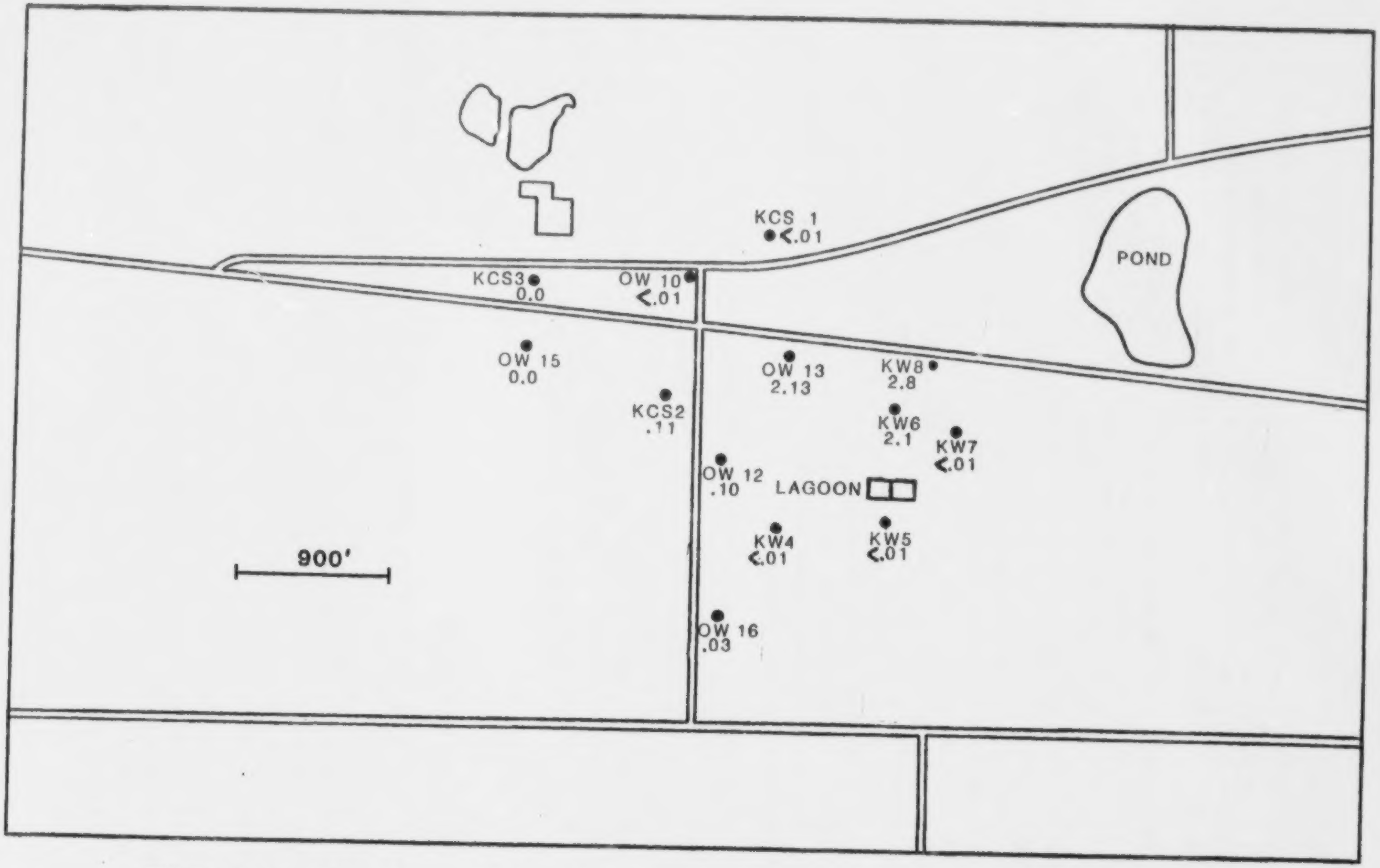
KCS 1
<.01
POND
KCS3
0.0
OW 10
<.01
OW 15
0.0
OW 13
2.13
KW8
2.8
KCS2
.11
KW6
2.1
KW7
<.01
OW 12
.10
LAGOON
KW4
<.01
KW5
<.01
900'
OW 16
.03

FIGURE 8-44 Observation well locations and associated total chromium levels (ppm) in May 1982.

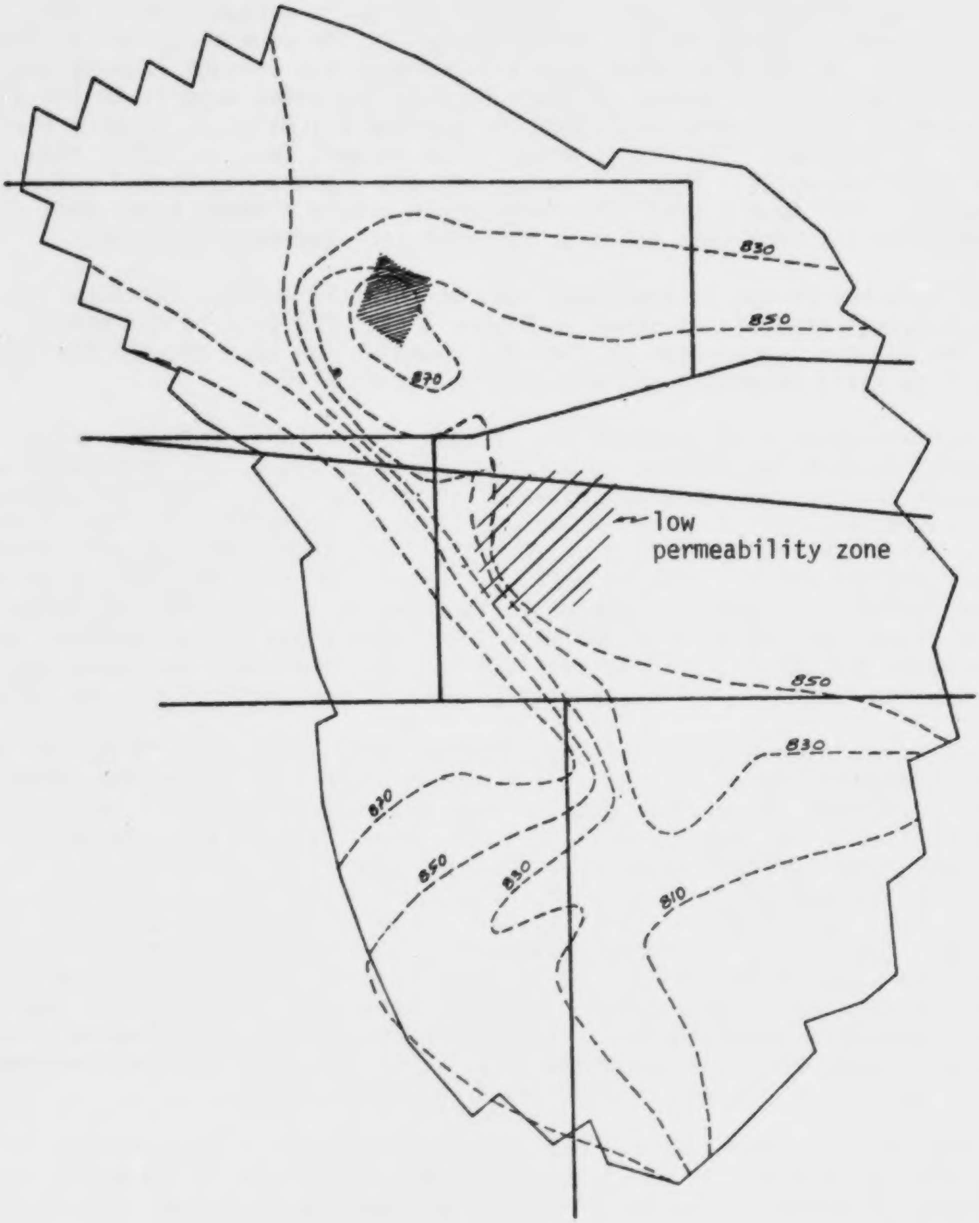
830
850
870
low permeability zone
850
830
830
850
830
810

FIGURE 8-45 Revised aquifer bottom contours and low permeability zone.

Sensitivity analyses were run varying the hydraulic conductivity and shape of the low permeability zone. The final hydraulic conductivities were in the range of 20-27 ft/day, about 1/4 to 1/5 the general hydraulic conductivity. It was also noted that a laundromat had seepage lagoons just north of well KW-5. Review of their Monthly Operating Reports to the DNR concerning the discharge indicates the average discharge is no more than 4,000 gallons/day. The static water level in well KW-5 is higher than the other new wells. This possibly indicates a mound has formed under the lagoons. That such a small discharge would create a mound also lends support to the idea that the area contains less permeable material.

This information was incorporated into the AQUIFEM model. The flow field was altered somewhat, as shown in Figure 8-46. The grid is too coarse in the laundry lagoon area to show any mounding for such a small discharge. The flow field is consistent with current information.

A careful analysis was made of the seepage velocities. Several streamlines passing through key monitoring wells were investigated. A representative seepage velocity was selected for each streamline. The locations of peak concentrations and other key measurements were estimated along the streamline using the representative velocities. The streamlines and estimated locations are shown in Figure 8-47. It should be noted that the velocities were determined without reference to the chemical data. Once the velocities were fixed, the chromium values were translated along the streamlines to determine the relationship between the revised flow model and known contamination locations. The analysis of each streamline is discussed separately.

Along streamlines A and B a representative velocity of 1.25 ft/day was used. The interpretation of one major slug moving along this streamline seems consistent with the quality data. Peaks recorded at wells V-1 and MW-1 are consistent in magnitude (11 ppm) and travel time between the wells. A higher peak (20 ppm) measured at WW-4 in June 1979, generally fits in with the passage of the same peak, although its magnitude is greater. The April 1980 measurement at OW-12 appears to be on the trailing edge of the plume. Translating all these measurements down the streamline indicates that the plume is past KW-4. It is surprising no chromium was found in KW-4; a very small concentration would be expected. Model results are then reasonably consistent with the interpretation of a slug moving along these streamlines. The projected location of the plume peak was recommended as a location to install an additional monitoring well.

A velocity of 0.75 ft/day was used along streamline C. Measurements from F-1 are not necessarily consistent with what appears to be happening downstream. Movement of the April 1980 measurement is consistent with KW-6. If the 1977 measurement in F-1 (0.33 ppm) was associated with a very sharp peaked slug, or a slug that otherwise missed F-1, then it also is consistent with KW-6. There was another measurement of 0.33 ppm in WW-2, near F-1, in June 1979. If this was the forerunner of another slug, it is fairly consistent with the current measurement in OW-13. Translating peak measure-

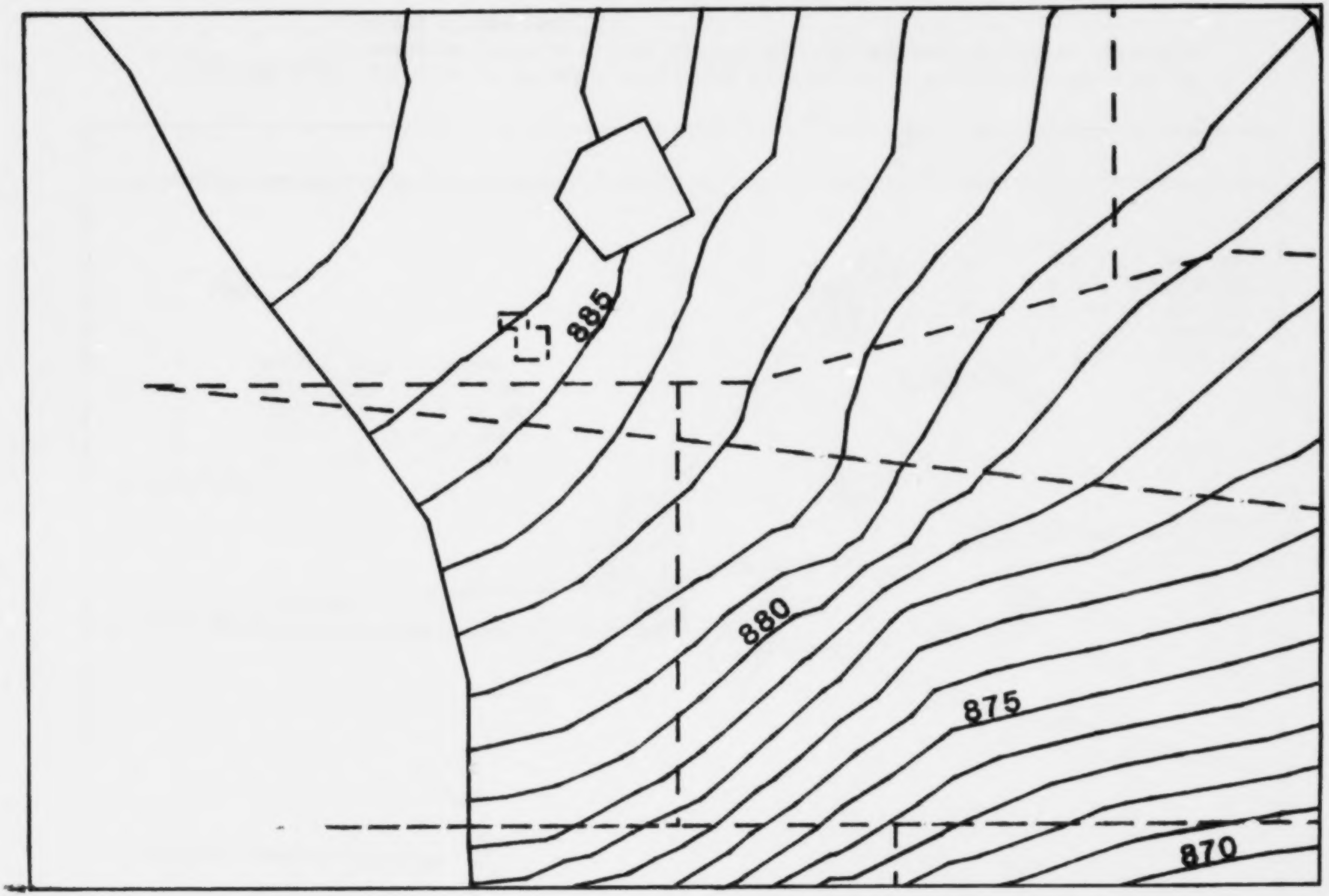
885
880
875
870

FIGURE 8-46 Simulation piezometric contours incorporating May 1982 field data.

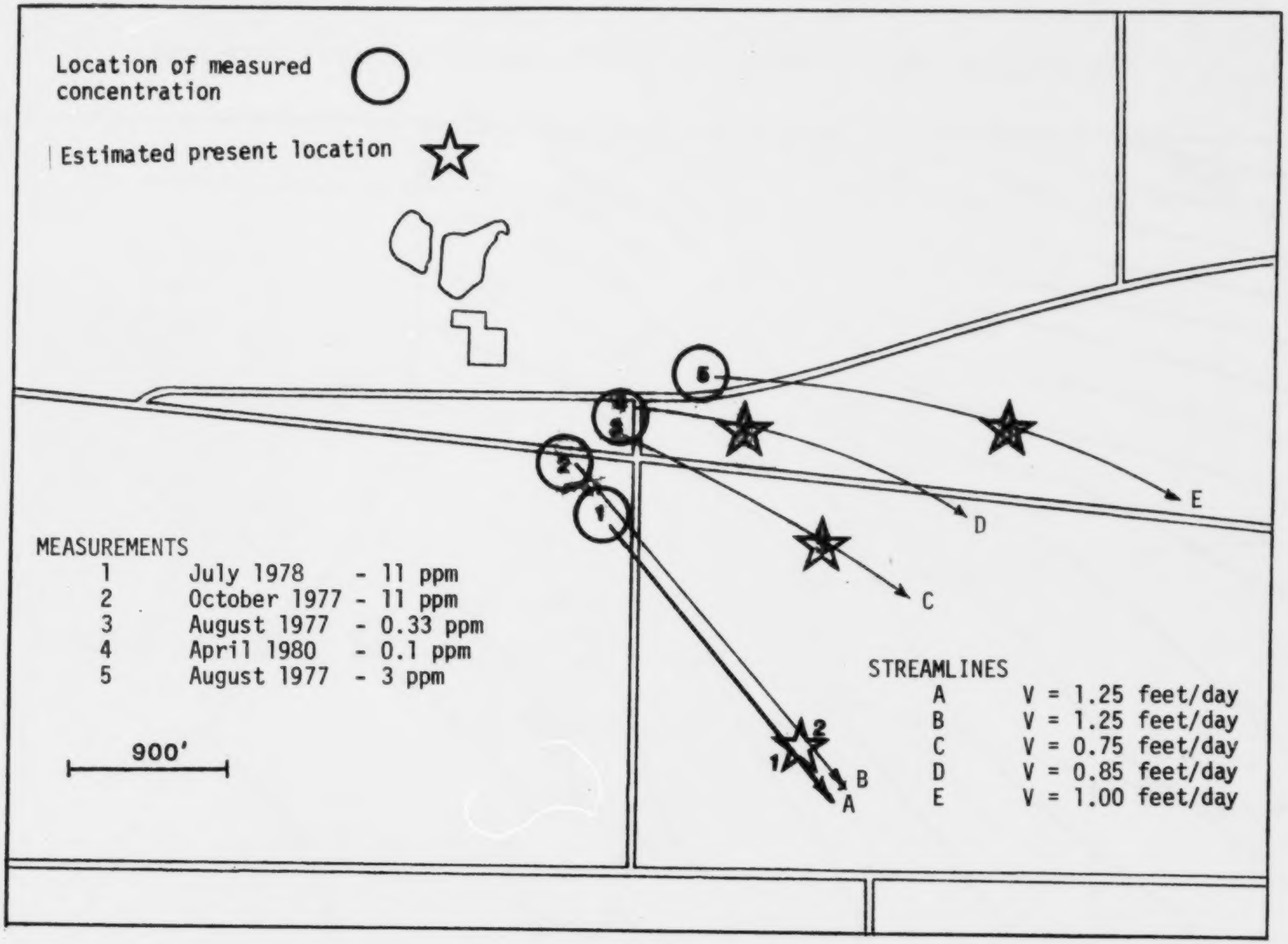
Location of measured concentration
Estimated present location
MEASUREMENTS
1 July 1978 - 11 ppm
2 October 1977 - 11 ppm
3 August 1977 - 0.33 ppm
4 April 1980 - 0.1 ppm
5 August 1977 - 3 ppm
900'
1
2
3
4
5
A
B
C
D
E
STREAMLINES
A V = 1.25 feet/day
B V = 1.25 feet/day
C V = 0.75 feet/day
D V = 0.85 feet/day
E V = 1.00 feet/day

FIGURE 8-47 Analysis of chromium data along streamlines. The present location of measured chromium values was estimated using representative velocities along streamline.

ments along this streamline would indicate the peaks have not yet reached KW-7. A small amount of chromium representing the plume front would not have been unexpected in KW-7, but based on the projections no further wells were recommended beyond KW-7 along this streamline.

A velocity of 1 ft/day was used along streamline E. High chromium concentrations were measured in G-1 during the summer of 1977. It is not known if these were peak values because the subsequent measurements consistently declined and there were no earlier measurements. The 1977 measurement was translated along this streamline and used as a basis for recommending locations of additional wells.

Keck was receptive to recommendations based on the computer analysis. They recognized that the model incorporated the known data and reasonable assumptions extrapolating the data and estimating boundary conditions. The simulation provided the best available approximation of the real system. While there are still many unknowns, no better analysis was available without additional information. And this analysis recommended well locations further away from PPP than they were originally planning based on hand calculations. The model also helps provide a plausible interpretation of the situation, that fits the data.

Field Data and the Recalibration of AQUIFEM

Additional field work was conducted in June and July 1982. The piezometric head contours and location of the principal plume, based on the new wells, is shown in Figure 8-48. It is not clear if the actual front edge of the plume has been identified. Both wells KW-16 and KW-18 have reported levels of 0.03 ppm total chromium. The highest concentrations are oriented along an east-west axis between OW-13 and KW-11.

Monitoring well placement based on model projections was successful. High concentrations were found as far east of the site as projected. Low concentrations were found in OW-16 and KW-16 southeast of PPP, but not the high concentrations projected. It is not clear what happened to the high peak concentration that was observed in domestic wells WM-1 and V-1 in 1977 and 1978, and OW-12 in 1980. Additional analysis of the possible flow paths is discussed later.

The additional wells provided more detailed information about the local hydrogeology. Another area where the aquifer pinches out was identified, areas with different hydraulic conductivities were defined, and the aquifer bottom elevations were better defined (see Figure 8-49). There is a large area southeast of PPP with low hydraulic conductivity, and an east-west "channel" roughly along the road with a very high hydraulic conductivity.

The information was incorporated into AQUIFEM, and the model was recalibrated against all the known information. This included seepage from the laundromat

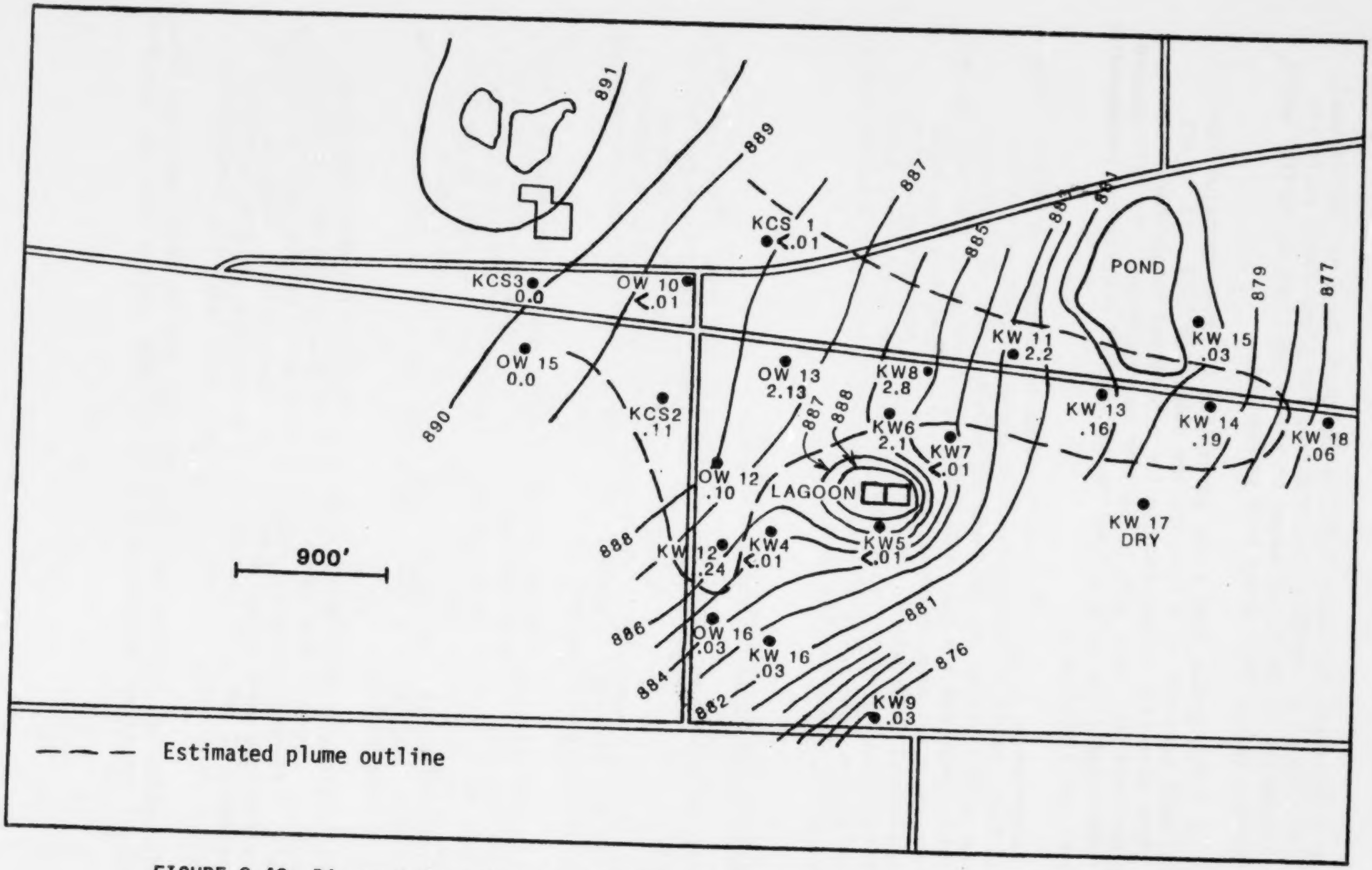
891
889
887
885
883
881
879
877
890
888
887
888
886
884
882
881
876
KCS 1
<.01
KCS3
0.0
OW 10
<.01
OW 15
0.0
KCS2
.11
OW 13
2.13
KW8
2.8
KW 11
2.2
POND
KW 15
.03
KW 13
.16
KW 14
.19
KW 18
.06
KW6
2.1
KW7
<.01
OW 12
.10
LAGOON
KW 17
DRY
KW 12
.24
KW4
<.01
KW5
<.01
OW 16
.03
KW 16
.03
KW9
.03
900'
Estimated plume outline

FIGURE 8-48 Piezometric contours and measured total chromium (ppm) at observation wells during summer 1982.

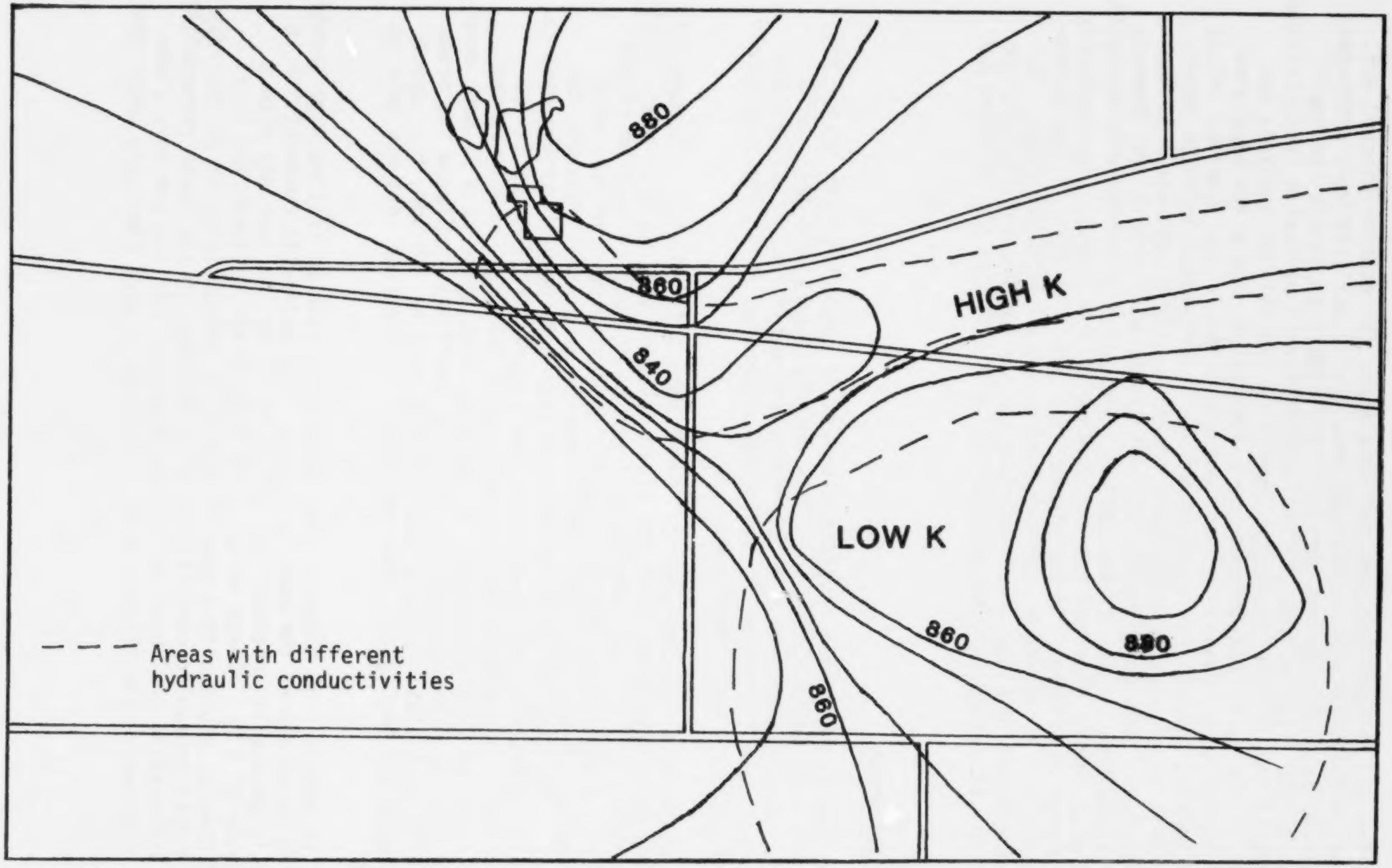
880
860
840
HIGH K
LOW K
860
880
860
Areas with different hydraulic conductivities

FIGURE 8-49 Final aquifer bottom contours and areas with different hydraulic conductivities.

lagoons of 4,000 gallons/day, and the area where the aquifer pinched out. During the calibration process various sensitivity analyses were conducted. The hydraulic conductivity was varied in the highly permeable "channel", the width of the "channel" was varied, and different hydraulic conductivities were tried at the eastern and western ends. A sensitivity analysis was also made of the specified head boundary conditions. Once the simulated piezometric heads and seepage velocities were close to the observed values the pond located between KW-12 and KW-15 was incorporated into the model. This was done as a check by specifying the piezometric head equal to the pond elevation. Such an approach "forced" the model to match the observed heads by withdrawing water at that point. The water withdrawn was reasonably close to what may be expected for evapotranspiration losses. The hydraulic conductivities used were: in the channel K = 125 feet/day, in low permeability areas K = 25 feet/day, and the general area K = 85 feet/day. The results are shown in Figure 8-50, without the pond being artificially included. The simulated aquifer behavior is very close to the observed behavior.

Model Application

The next step in the field investigation was to conduct a pump test. The pumping well was to be placed in highly contaminated water near OW-13. There was concern about where to discharge the water, and if it was discharged back into the plume, it had to be determined if it would adversely affect the spreading of the plume.

A local scale model was designed to investigate this problem. The boundary conditions were determined from the field data and the regional model simulation (Figure 8-51). The pumping well was to be located near OW-13 and the water recharged back into the heavily contaminated area near KW-8. Small elements were placed near these sites to accurately simulate the situation. The grid was also designed so that node points corresponded to observation wells for easy comparison (see Figure 8-52 for the finite element grid). A steady state simulation with the local model yielded results close to observed heads. An unsteady simulation of a 24 hour pump test was run, and the decay of the recharge mound was simulated for seven days. With a simulated pumping and recharge rate of 150 gpm, the impact of the mound was negligible after one week. So the pump test was able to proceed.

Analytical models (the commonly used techniques such as fitting type curves) were used to interpret the pump test data. The hydraulic conductivity in the highly permeable "channel" was estimated to be 160 feet/day with a storativity of 0.16. These values were used in the regional and local AQUIFEM models, along with a general hydraulic conductivity of 85 feet/day and a revised hydraulic conductivity of 5 feet/day in the lower permeability area. The results are shown in Figures 8-53 and 8-54 and are very close to the observed values (Figure 8-48). A mound is even simulated under the

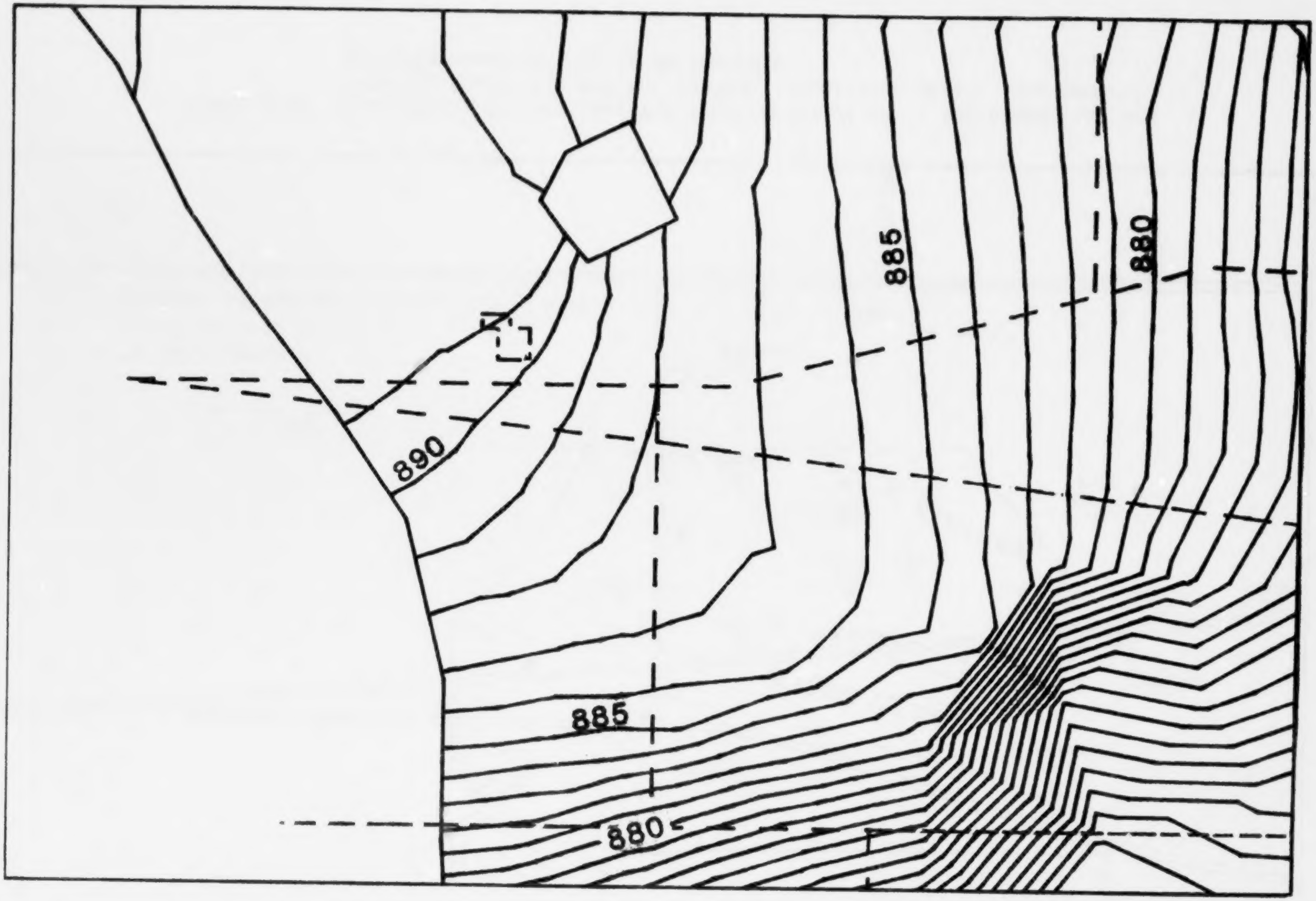
890
885
880
885
880

FIGURE 8-50 Simulated piezometric contours after AQUIFEM was recalibrated using July 1982 field data.

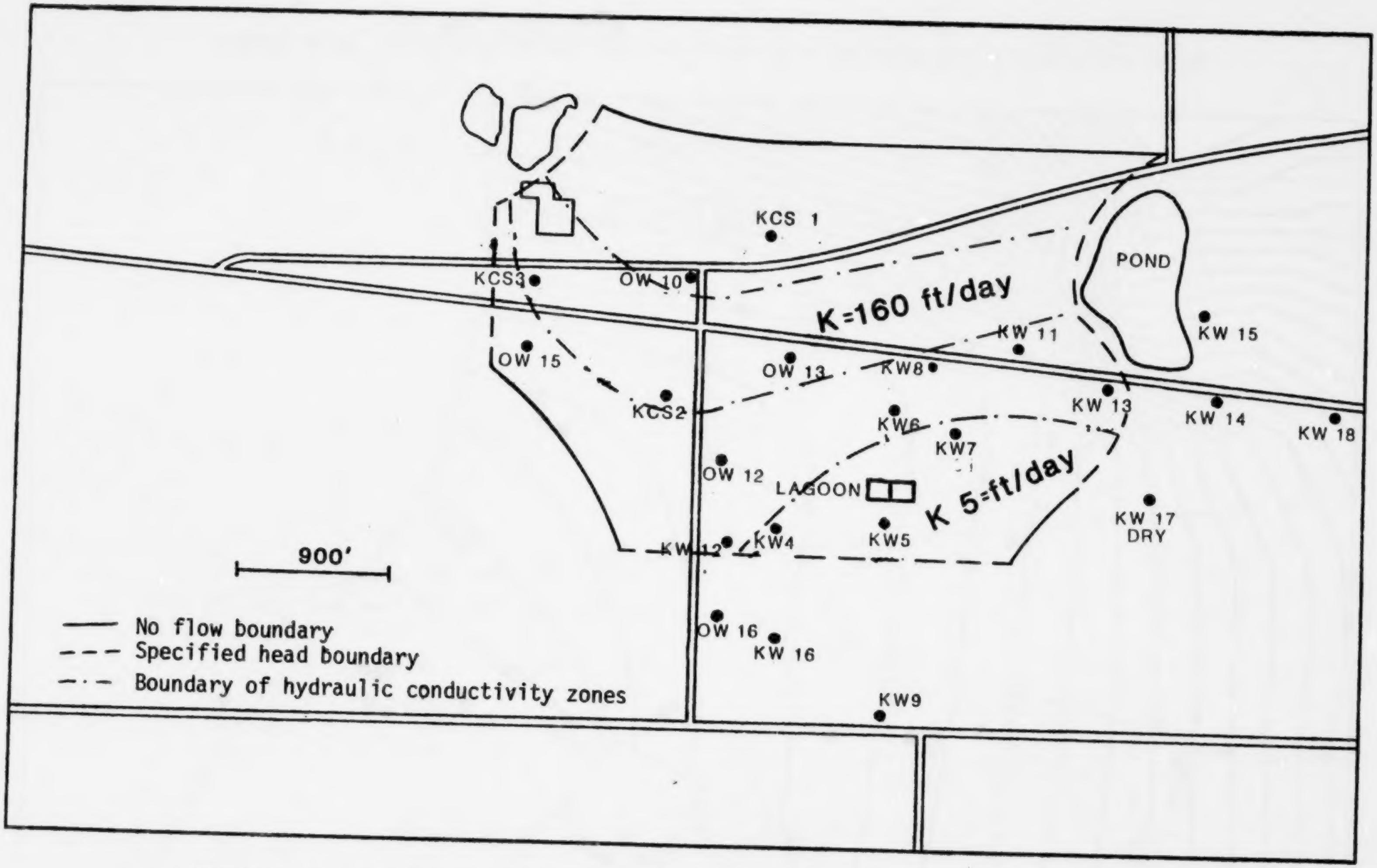
KCS 1
POND
KCS3
OW 10
K=160 ft/day
KW 11
KW 15
OW 15
OW 13
KW8
KW 13
KW 14
KW 18
KCS2
KW6
KW7
OW 12
LAGOON
K 5=ft/day
KW 17
DRY
KW 12
KW4
KW5
900'
OW 16
KW 16
KW9
No flow boundary
Specified head boundary
Boundary of hydraulic conductivity zones

FIGURE 8-51 Boundary conditions used for local model of PPP. The boundaries are based on field data and the regional simulation model. The general hydraulic conductivity is 85 feet/day.

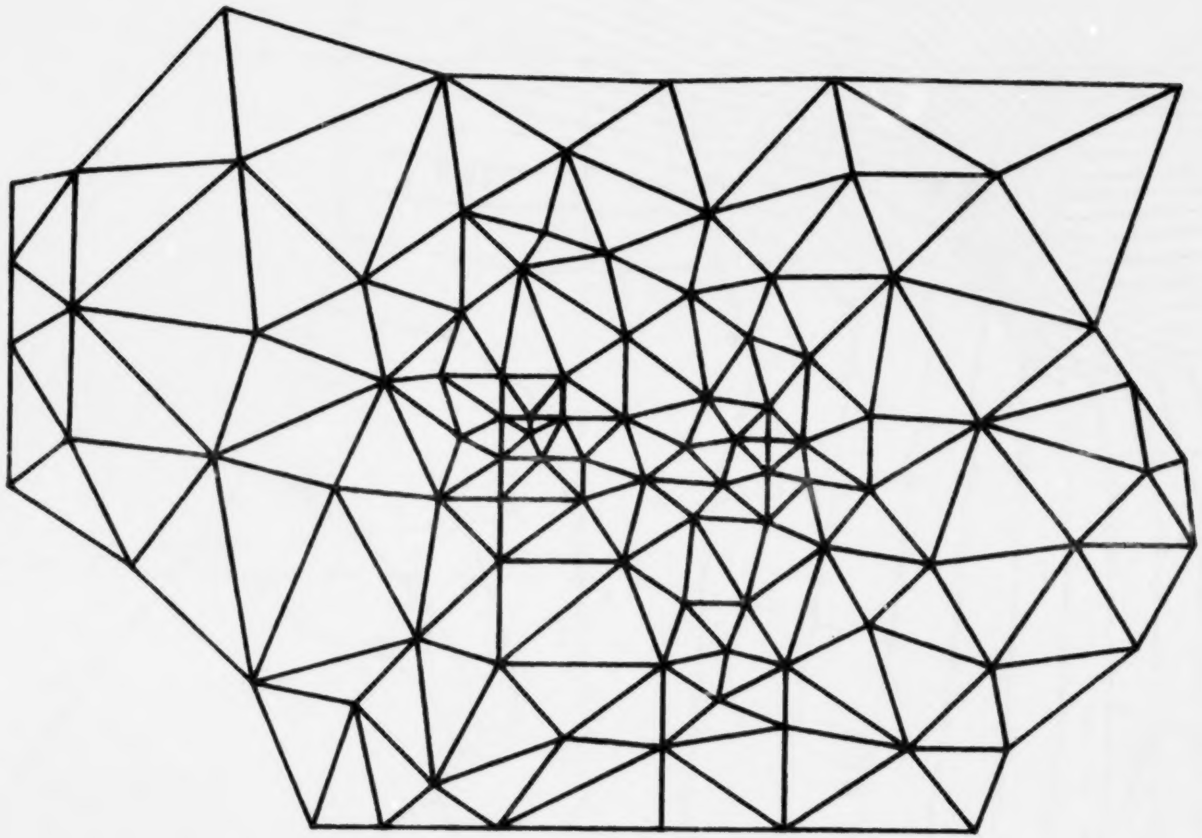

FIGURE 8-52 Finite element grid used for local model at PPP.

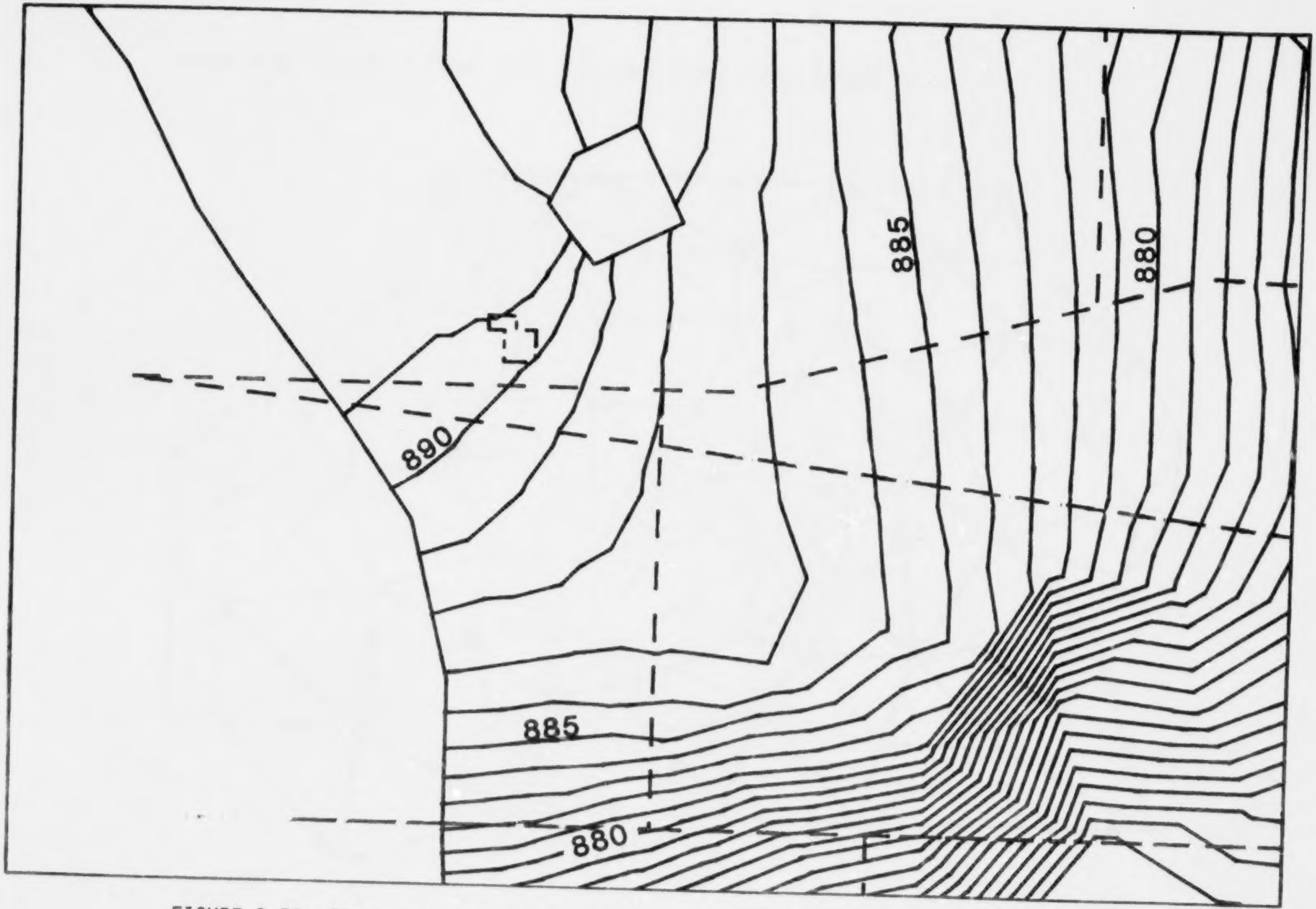

FIGURE 8-53 Final simulation piezometric contour map. The simulated aquifer behavior is very close to observed. The final adjustments of aquifer parameters were based on the pump test.

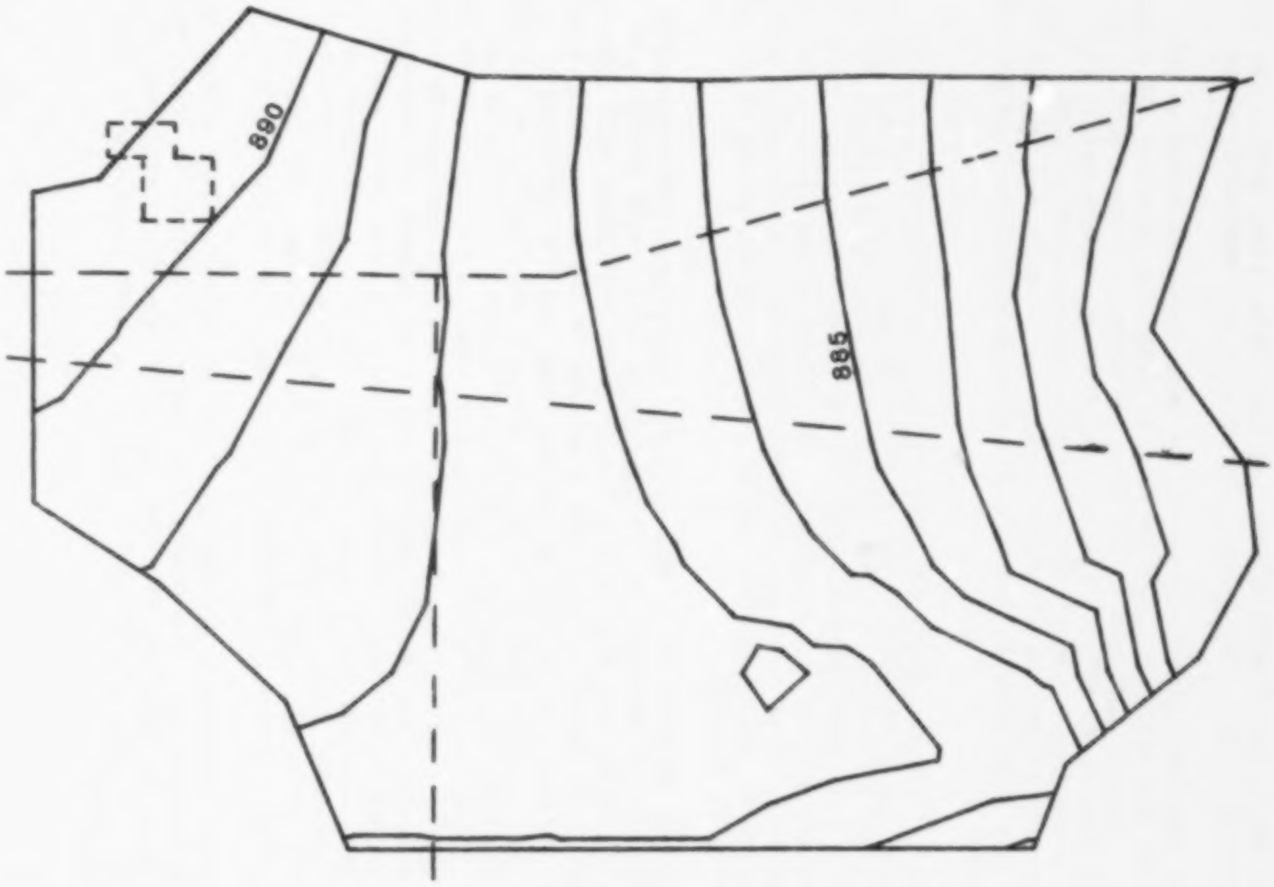

FIGURE 8-54 Final simulation piezometric contour map using the local model. The final adjustments of aquifer parameters were based on the pump test.

laundromat lagoons. For comparison, the local model was also used to simulate the pump test. Pumping rates (105 gpm), pumping well, observation well and recharge locations were all set as they were in the actual pump test, and aquifer properties were the same as in the above simulations. The results are compared with actual pump test data, along with a run using a storativity of 0.10 in Table 8-5. The results are reasonably close.

Streamlines that the chromium might follow were developed based on the final AQUIFEM simulations. The flow path is sensitive to where the source is located. Several possible streamlines are shown in Figure 8-55. The streamlines that could affect wells V-1 and WM-1 are unfortunately right at a point where they could either ultimately travel south or east. The present location of peak concentrations measured in wells G-1 (August 1977) and WM-1 (July 1978) were estimated using seepage velocities from AQUIFEM (Figure 8-55).

The USGS Mass Transport Model was used to try to evaluate where a plume would go when the known flow field was fully incorporated. It was updated with the latest hydrogeologic information. The flow field matched AQUIFEM's very closely. The model demonstrated that the plume would split, with part going south and most of it going east. The amount of the split is sensitive to the source location. Figure 8-56 presents the estimated current plume location based on the USGS model. It is a similar distribution to what has been observed in the field.

The final model application of the study was to evaluate alternate purge well configurations and begin preliminary purge well system design. It was necessary to use unsteady simulation for some high purge well pumping rates. Apparently numerical problems developed in the steady state solution because of the combination of high pumping rates and low saturated thickness in some areas. A time step of two weeks was used and the figures represent the simulated water table after six months of pumping. A range of pumping rates were tried. Two effective systems are shown in Figures 8-57 and 8-58. The first used a pumping rate of 120 gpm near OW-13, 60 gpm near KW-14 and 30 gpm near KW-12. The second used the same total pumpage but redistributed it and moved the eastern well near KW-11. The wells near OW-13 and KW-11 pumped 90 gpm, and near KW-12 pumped 30 gpm. The final simulation was an attempt to purge the plume in about six months (Figure 8-59). A battery of seven pumping wells were used pumping a total of 360 gpm. The pumping rates vary with location and permeability of the surrounding aquifer.

The model will continue to be used to assist in the purge well system design and implementation. The models have been very helpful in interpreting the field data, coordinating with the field work and evaluating management alternatives. A very complex aquifer system has been successfully simulated in this case study.

TABLE 8-5

Comparison of simulation pump test to drawdown (feet) measured in field. The pumping rate was 105 gpm, two storativities were simulated, S=0.16 and S=0.10. The pumping well was located 200 feet west of OW-13, the first observation well (01) was located 30 feet further upgradient and the second observation well (02) located 93 feet upgradient from the pumping well. Simulation drawdowns are not at all similar to drawdown in the pumping well because the model does not include well losses and it averages the drawdown over an element. The simulated drawdowns are reasonably good at the observation wells as time increases.

	PUMPING WELL			01			02			OW-13		
Time (min.)	field data	model S=.16	model S=.10	field data	model S=.16	model S=.10	field data	model S=.16	model S=.10	field data	model S=.16	model S=.10
30	8.73	.29	.35	.51	.07	.11	.18	.004	.01	-	.001	.002
60	8.85	.48	.56	.60	.17	.24	.18	.01	.03	.03	.003	.01
90	8.90	.56	.64	.62	.25	.33	.21	.03	.06	.03	.01	.02
120	8.92	.62	.71	.67	.31	.39	.24	.05	.08	.04	.01	.03
210	8.98	.73	.83	.71	.41	.50	.27	.10	.16	.06	.03	.06
300	9.06	.81	.90	.84	.48	.57	.31	.14	.22	.08	.05	.09
390	9.08	.86	.96	.80	.53	.63	.34	.19	.26	.10	.07	.11
480	9.11	.90	1.00	.81	.58	.67	.37	.22	.30	.11	.09	.14
630	9.14	.96	1.06	.85	.63	.73	.41	.27	.35	.12	.12	.18
780	9.2	1.01	1.10	.88	.68	.77	.45	.31	.39	.16	.14	.21
830	-	-	-	.93	-	-	.47	-	-	.17	-	-
930	-	1.04	1.14	-	.71	.81	-	.34	.43	-	.17	.25
1080	-	1.07	1.17	-	.74	.84	-	.37	.46	-	.19	.28
1290	-	1.11	1.21	-	.78	.88	-	.40	.50	-	.22	.31

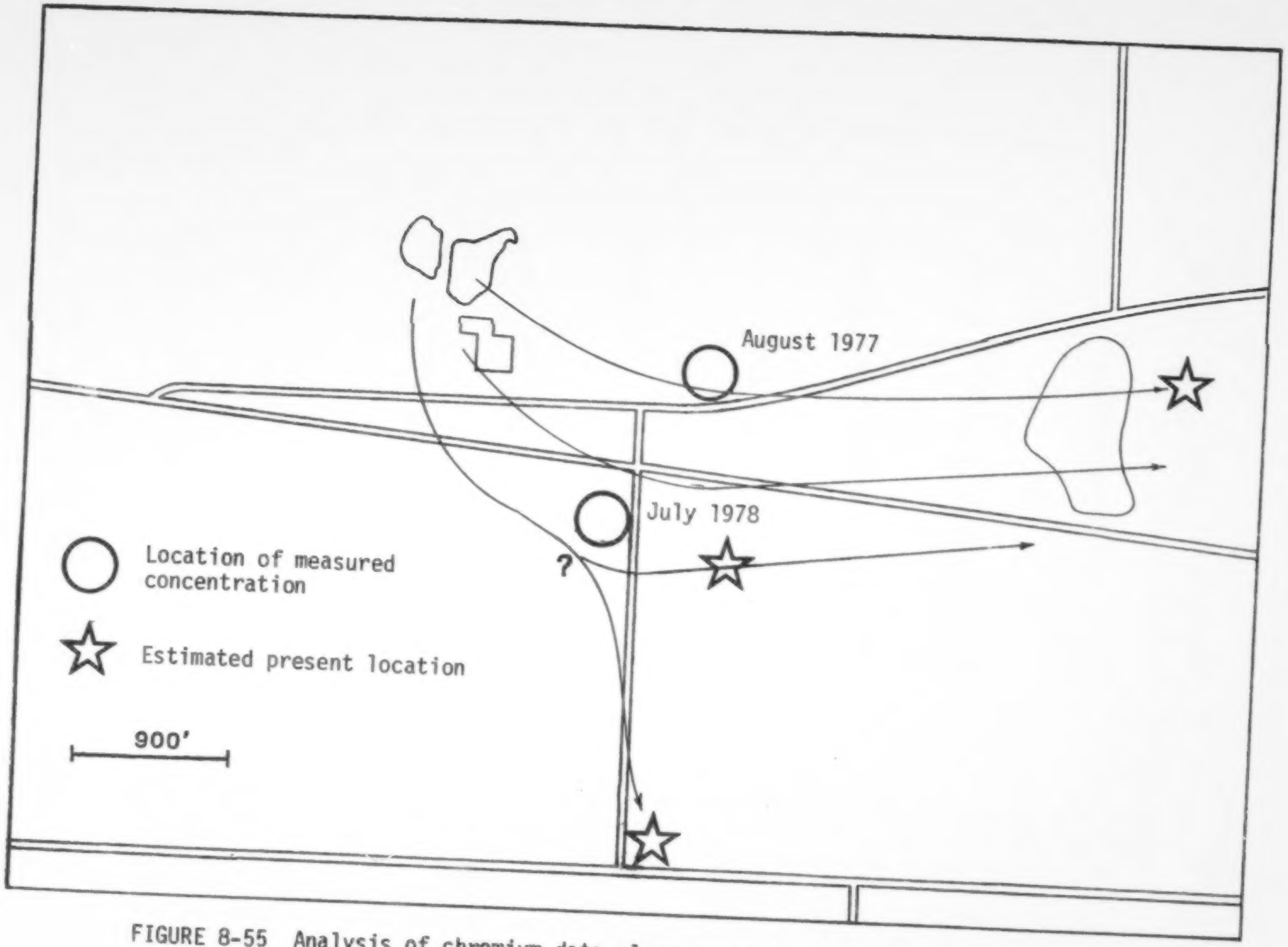
August 1977
July 1978
?
Location of measured concentration
Estimated present location
900'

FIGURE 8-55 Analysis of chromium data along possible streamlines. The streamlines and seepage velocities are from the final regional AQUIFEM simulation. The flow path is sensitive to source location.

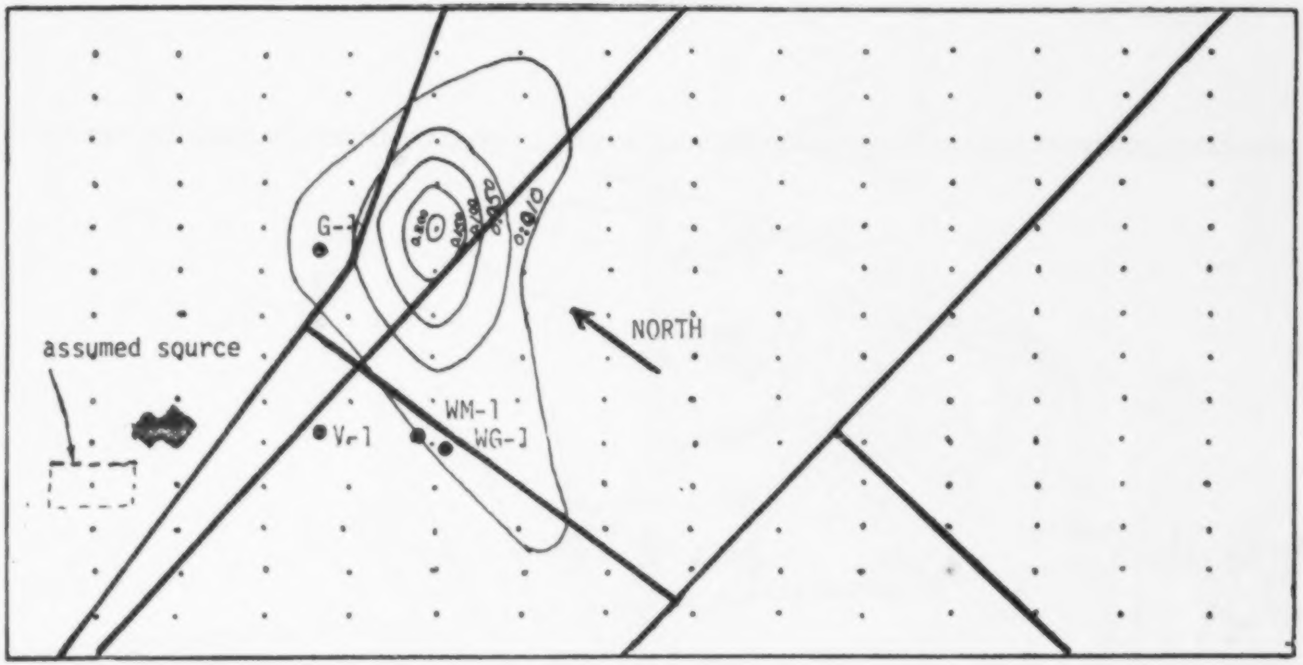

FIGURE 8-56 Relative concentration (C/C_0) contours from the USGS Mass Transport Model. The model was updated with the new field and pump test data. The results represent simulated current conditions. The grid is coarse and therefore misses some of the available hydrogeologic detail. The simulated peak passed near well V-1, but the same peak concentration did not pass through WM-1 as had actually been observed. This still leaves some question about the observed plume's final path. The path is sensitive to source location.

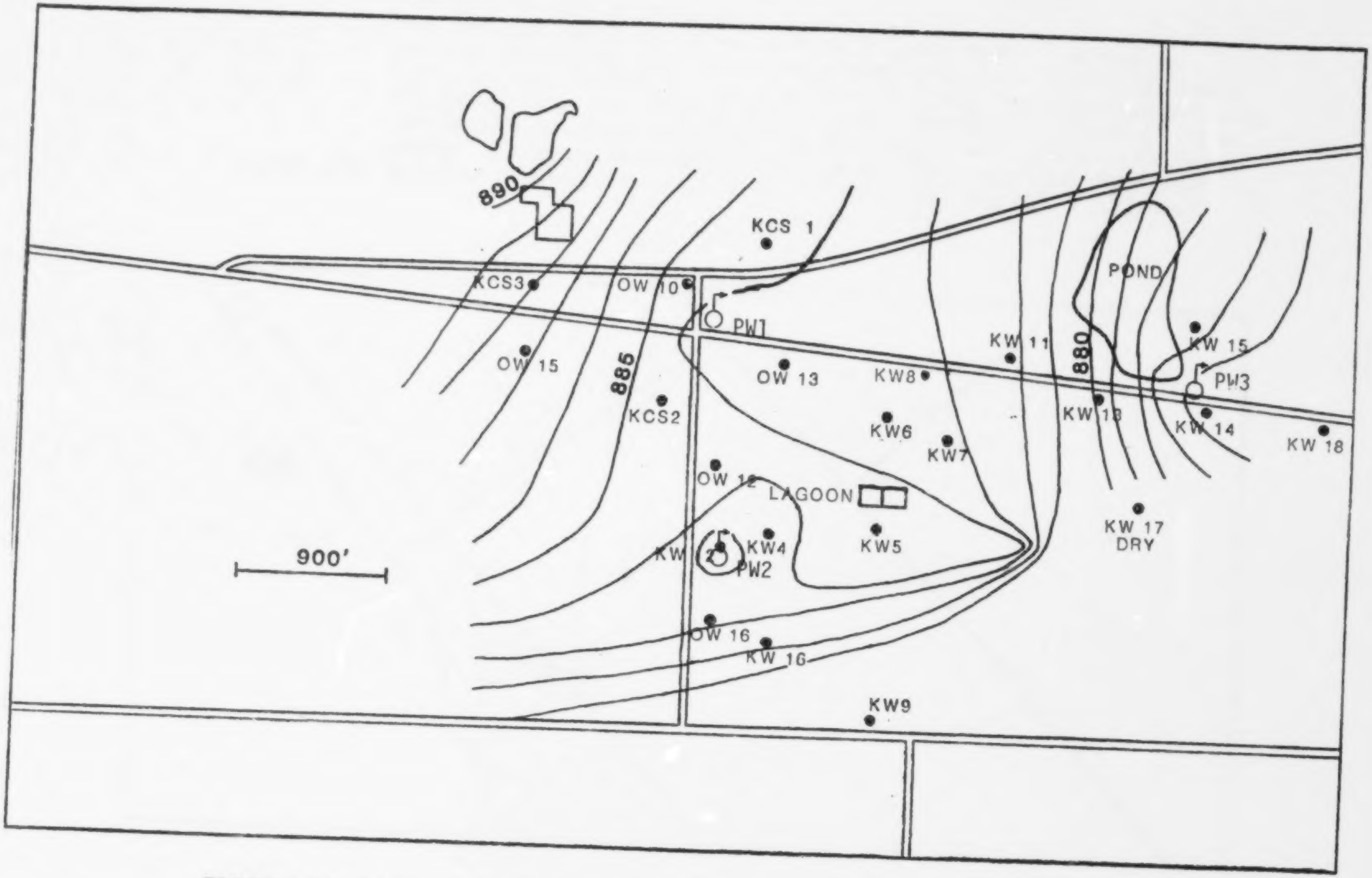
890
885
880
KCS 1
KCS3
OW 10
PW1
OW 15
OW 13
KCS2
KW8
KW 11
POND
KW 15
PW3
KW 13
KW 14
KW 18
KW6
KW7
OW 12
LAGOON
KW 17
DRY
KW 2
KW4
PW2
KW5
OW 16
KW 16
KW9
900'

FIGURE 8-57 Piezometric contours after six months of pumping this purge well configuration. The pumping rates were PW1 = 120 gpm, PW2 = 30 gpm and PW3 = 60 gpm.

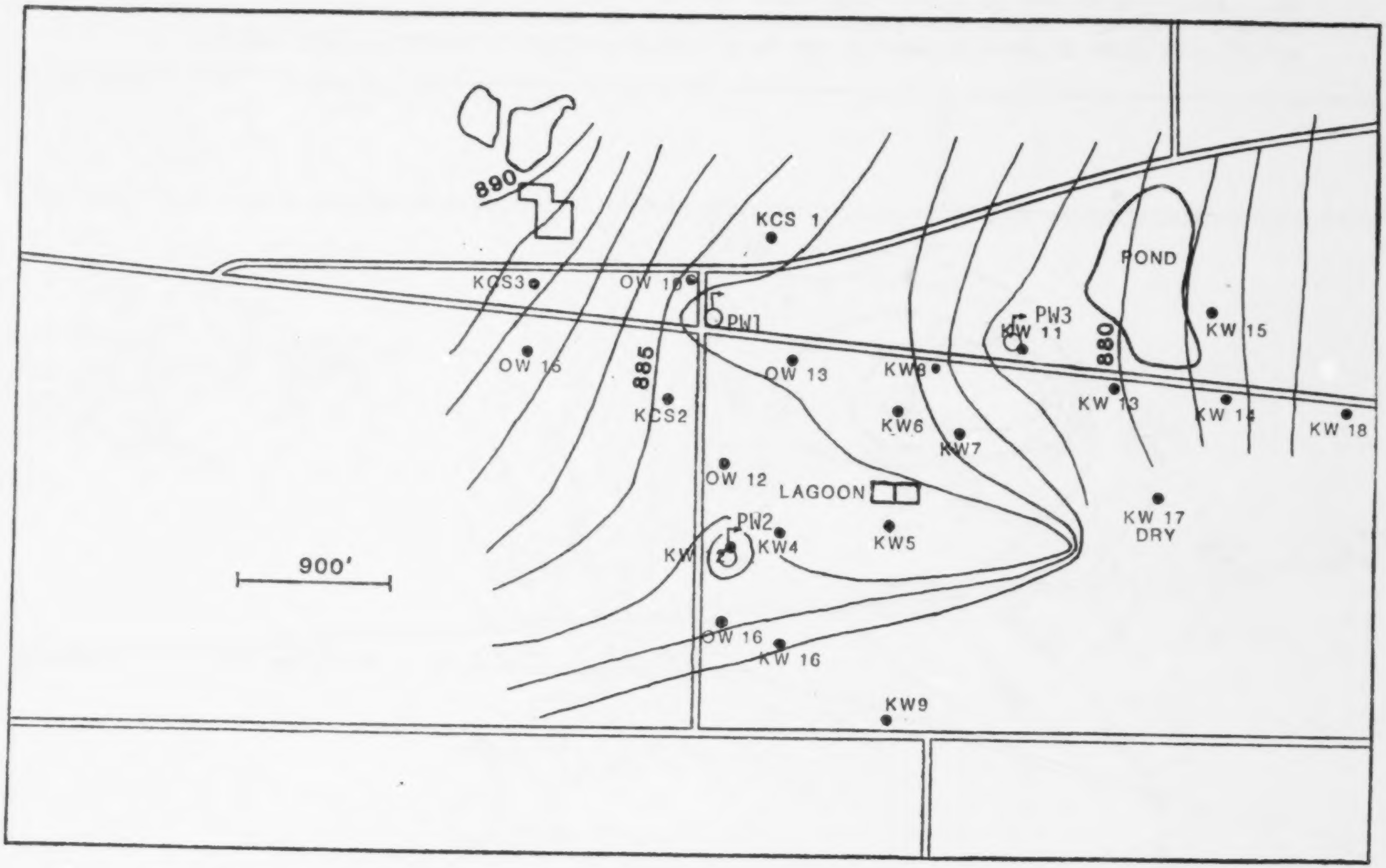
890
KCS 1
KCS3
OW 10
PW1
OW 15
885
KCS2
OW 13
KW8
KW6
KW7
OW 12
LAGOON
PW2
KW4
KW
KW5
OW 16
KW 16
KW9
PW3
KW 11
880
POND
KW 15
KW 13
KW 14
KW 18
KW 17
DRY
900'

FIGURE 8-58 Piezometric contours after six months of pumping this configuration. The pumping rates were PW1 = PW3 = 90 gpm and PW2 = 30 gpm.

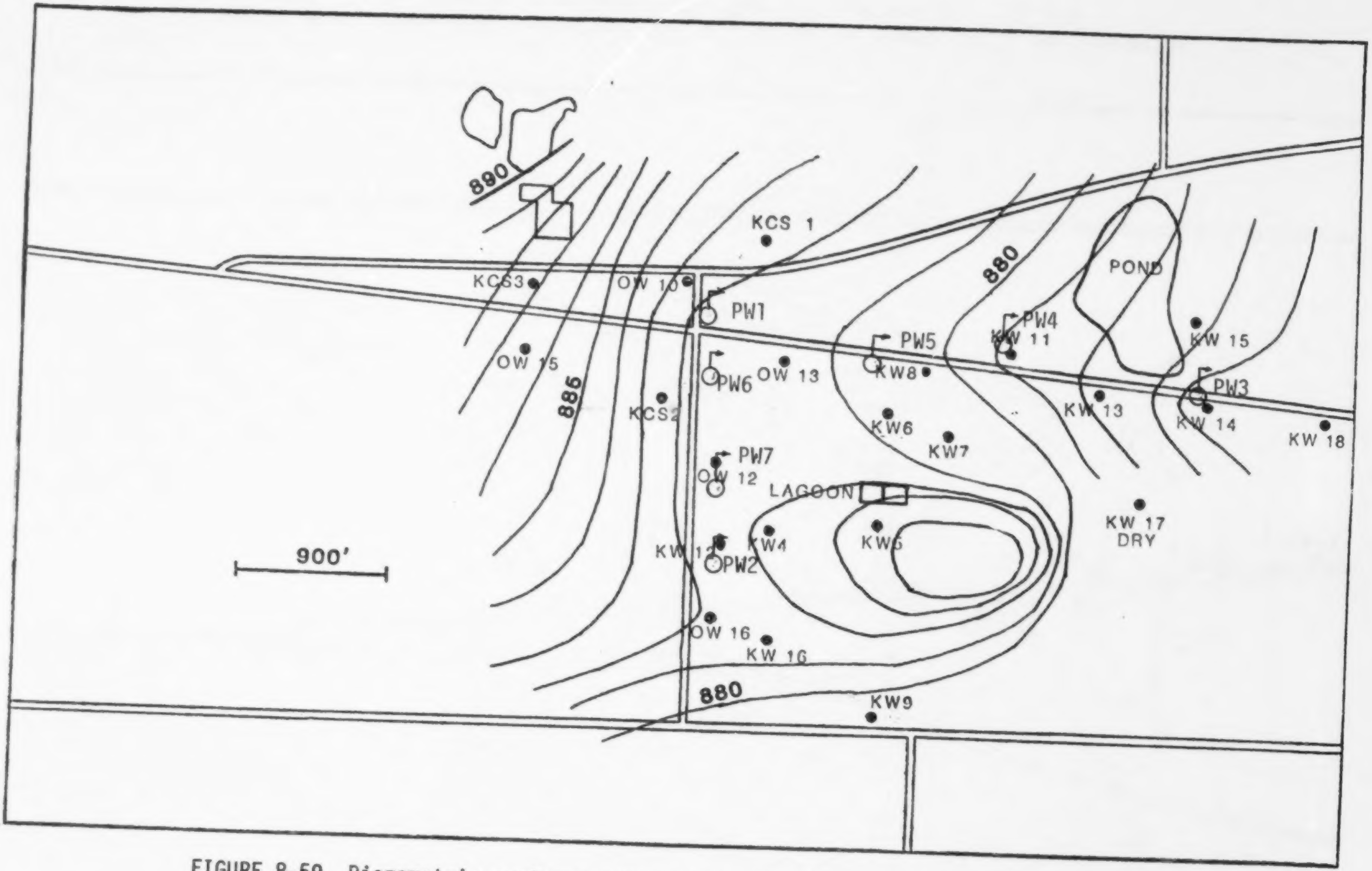
890
KCS 1
KCS3
OW 10
PW1
OW 15
885
KCS2
PW6
OW 13
PW5
KW8
880
PW4
KW 11
POND
KW 15
PW3
KW 14
KW 18
KW 13
KW6
KW7
PW7
OW 12
LAGOON
KW 17
DRY
KW 12
KW4
KW5
PW2
900'
OW 16
KW 16
880
KW9

FIGURE 8-59 Piezometric contours after six months of pumping based on purge well system designed to purge the plume in approximately six months. The total pumping rate is 360 gpm, PW1 = 90 gpm, PW2 = PW6 = PW7 = 30 gpm and PW3 = PW4 = PW5 = 60 gpm.

SECTION V

EVALUATION & CONCLUSION

CHAPTER 9

EVALUATION

Groundwater modeling has proved to be an effective tool in analyzing contamination sites found in Michigan. With the models, many of the known complexities of the groundwater system can be incorporated into the analysis. This leads to more realistic analysis, and the impacts of management decisions can be simulated.

Groundwater modeling is a very sophisticated tool. Groundwater modeling is a multi-disciplinary field incorporating elements of: hydrology (both surface and groundwater), geology, hydraulics, mathematics, and computer science. The interaction of these elements must be fully appreciated by those planning to apply groundwater models. Development of a program to utilize groundwater computer simulation requires expertise in these disciplines, and proper management and technical support.

Flow models are developed to the point that they yield very accurate solutions to the input problem. The parameters used are well understood and generally measurable. However, measured parameters must be interpreted in light of limitations inherent in the measuring techniques. For example, soil samples taken for laboratory determination of hydraulic conductivity are invariably altered from their natural state. Experience has indicated that laboratory hydraulic conductivities are frequently only one-third to one-fifth the actual field value. Data limitations represent the real limitation to flow model accuracy.

There will always be uncertainty in defining a groundwater system. Because it is underground, observation is generally restricted to single points at monitoring wells. Complex geologic formations may result in large changes in aquifer characteristics just a short distance from the observation points. Since there will always be uncertainty, it is largely a question of degree to assess how much uncertainty is acceptable in solving the problem at hand. Groundwater modeling greatly assists in the analysis because it incorporates the effects of assumptions and extrapolations. Through sensitivity analysis these effects can be carefully evaluated. Models also provide a means of evaluating whether the preliminary understanding of the groundwater system makes sense or not.

Mass transport models are not as well defined as flow models. There are still problems in the numerical solution techniques; and the physical phenomena are not fully understood. Despite their limitations, mass transport models do allow some reasonable analysis of the dispersion/diffusion process, which obviously exists and plays an important role in many cases. The most important aspect of mass transport modeling is the flow field determination. An accurate flow model is the foundation of any reasonable mass transport analysis.

Several mass transport modeling approaches were used in this study. The principal techniques were direct analytical solution of very idealized conditions, use of a finite element formulation, and use of a method of characteristics formulation.

The remainder of this chapter discusses some important general considerations in model use and briefly evaluates the models used in this study.

Boundary Conditions

Boundary conditions are critical to the solution of a groundwater model. They determine the overall solution, and if they are set too close to the area of interest, may completely dominate the solution. There is usually little or no information directly defining the boundary conditions. In this study they were usually determined by assuming groundwater interrelationships with the surface hydrology and topography. Each case involved water table aquifers. It was assumed that nearby lakes and streams were the aquifer discharge points and specified head boundaries equal to the surface water elevation were used. Aquifer discharge can also be compared with known base flow along a river, as it was in Comstock. Major topographic highs were assumed to form groundwater divides and since no flow crosses a divide, no flow boundaries were assumed. These reasonable assumptions seemed to work well for the case studies.

At Southwest Ottawa County Landfill, the problem was on a local scale, but there were no well defined natural boundary conditions for a local scale model. Since the local boundaries have a significant impact on the solution, it is important that they are reasonable. The regional model used Lakes Michigan and Macatawa as specified head boundaries, and estimated no flow boundaries from hydrologic considerations. It was used to establish the boundary conditions for the local model. Calibration involved iterating between the regional and local models until satisfactory boundary conditions were developed. This process worked very well. In almost textbook fashion, the simulation improved with each iteration. The use of physically based boundary conditions, relatively far from the areas of greatest interest, for a regional model also worked well at Production Plated Plastics. When more detailed simulation was required in a specific area, the results from the regional model were used to establish boundary conditions for a local model.

Sensitivity Analysis

Sensitivity analysis is a very important part of the modeling process. Where estimates are made in parameters or boundary conditions, the effects of possible error in the estimate should be analyzed. This is done by systematically varying values and evaluating the effects. When the results are not very sensitive, then the estimate does not require a high degree of precision. The relative importance of parameters and boundaries can be assessed and used to help direct additional field work. Sensitivity analysis also assists in the calibration process by isolating the effects of various estimates.

In any analysis it is important to carefully evaluate the full implications of the model results. Not only must piezometric heads be considered, but seepage velocities and discharge volumes as well.

Three-Dimensional Effects

Aquifers are three-dimensional systems and can locally have significant 3-D flow patterns. For example, there can be vertical gradients as flow diverges around a silt lens, and there are vertical gradients under a seepage lagoon. These effects can usually be ignored when larger scales are considered because aquifers typically have very small aspect ratios (depth ÷ lateral extent).

Nested monitoring wells at Southwest Ottawa County Landfill indicated vertical gradients in one area where a mound had formed. A 2-D flow model could not reproduce the mound, apparently because either the mound was transient or there were extreme 3-D effects. For the problem being analyzed, the 3-D effect was not significant. The piezometric heads were vertically averaged to approximate the conditions of a 2-D model. These transformed heads were then used for calibrating the 2-D model. Only a small area was affected by the transformation, but it did facilitate calibration. Care must be taken when dealing with 3-D effects; they are very complicated to analyze. Three-dimensional modeling is possible, but impractical for most situations. While it is usually possible to complete the desired analysis in only two dimensions, the third dimension should not be forgotten. It should be kept in mind that the 2-D analysis does not represent 3-D factors.

A resistivity survey proved to be a very valuable tool at Southwest Ottawa County Landfill. It gave a 3-D picture of a complex low permeability lens system. The information was incorporated into a 2-D model by assigning a confining layer where a lens was located at the aquifer top, a higher aquifer bottom elevation when at the bottom, and a lower permeability zone when the lens was continuous through the saturated thickness. This is a 2-D approximation because in the model only the transmissivity is changed by the variation in saturated thickness. It made an effective simulation of the flow field. Preferential flow paths through the lens system and diversion around the system that are expected in the real system were simulated in the model.

Steady and Unsteady State Simulation

Most of the modeling in this study used steady state conditions--the flow field does not change with time. Steady state simulation is cheaper to run and easier to analyze than unsteady simulation. For most natural conditions a steady state model is probably adequate. Groundwater systems tend to be highly damped and under natural conditions are relatively steady. There are seasonal fluctuations, but they tend to be uniform over the area and relatively small. The models used have the capability to simulate unsteady flow fields. This is important in modeling some man-made influences where new large stresses are introduced to the groundwater system. At Production Plated Plastics an unsteady simulation was made to investigate the effects of artificial recharge variation from a seepage lagoon and the influence of seasonal irrigation pumping. The model responded with a reasonable representation of the aquifer response to these stresses. If natural stresses such as seasonal aquifer recharge or seasonally changing boundary conditions were thought to be critical, then they could be modeled similarly. It was also necessary to use unsteady simulation for some high purge well pumping rates. Apparently numerical problems developed in the steady state solution because of the combination of high pumping rates and low saturated thickness in some areas. The steady state solution could be obtained after starting the simulation as a transient problem.

One application where an unsteady model is needed is in simulating a pump test. An attempt was made to simulate a proposed pumping test at Southwest Ottawa County Landfill. The pumping rate was too small for the finite element grid used. A finite element grid would have to be specifically to try to reproduce that particular small test. A larger scale aquifer test, one that would probably be performed in preparation for a full scale purge well system, probably would not require a greatly different finite element grid at Southwest Ottawa Landfill.

A local finite element grid was made to simulate a pump test at Production Plated Plastics. The pump test was simulated before it was run because of concern about recharge water forming a mound and causing the plume to spread out even further. The model showed there probably would not be any significant effect. So the pump test was able to proceed. The numerical model was not used as the primary tool in evaluating the raw pump test data. Analytical models (the commonly used techniques such as fitting type curves) were used to estimate hydraulic conductivity and storativity. The numerical model (using the estimated parameters) can be compared with the pump test results. Unless a very detailed grid is made, it is unlikely the numerical results can be expected to exactly reproduce a short term pump test. With a well designed grid, they should be reasonably close; and a sensitivity analysis can be performed.

Model Detail

Those comments on how the finite element grid relates to a pump test lead to a more general discussion of how much detail is appropriate for a model. In general the amount of data required for any project is that which sufficiently defines the nature and extent of the problem and meets the project goals. The modeling effort is tailored to fit the project. It is possible to get useful analysis with varying amounts of information.

A rather crude model was used at Comstock, commensurate with the available data and the initial project goals. The initial model was based on virtually no data, just a few domestic well logs and the surface topography. It was simple and relatively little time was put into it. Its primary value was to show how various assumptions concerning the boundary conditions would affect the flow field; i.e., primarily hypothesis testing. The initial model was not even close to the real situation. Once data became available, the simple model was updated and improved. It is extremely important to realize that a model is no better than the data it is based on. Useful analysis can be made with little data, but its validity must be kept in perspective with the data base.

The Comstock model was calibrated with the new field information. The model was kept simple so it could be easily updated as new data became available, and because the limited understanding of the aquifer system did not yet warrant greater detail. This approach worked well at Comstock. The model did not yield definitive results because the data base was not definitive. The level of effort was kept in proportion to the value of the analysis. The model helped put the data into perspective and did aid in understanding the aquifer system.

Much more detailed models were constructed for Southwest Ottawa and Production Plated Plastics. The data base gave a good picture of the local aquifer system and the models were able to relate this picture to the overall regional system. This in a sense extended the usefulness of the available data and created a credible representation of the situation. Again, the model is no better than the data base, as was discovered at Production Plated Plastics. New field data revealed a low permeability zone and a different aquifer geometry that could not have been extrapolated. However, the data were incorporated into the model, and the recalibrated model became an even more useful and accurate analytical tool. Incorporation of the new data was not a great task, but because of the model detail and complexity, it was not as simple as making changes in the Comstock model. The case studies at Southwest Ottawa and Production Plated Plastics merit the additional effort, and the more detailed and accurate models yield correspondingly more valuable results.

Coordination with Field Work

Part of this study dealt with coordinating the modeling process directly with field work. It proved to be beneficial but not without problems. In general, the models are able to analyze the current theories and physical interpretations of the field data, and provide an overall framework to examine the interrelationships between the data points and with known or suspected boundary conditions. As long as major "surprises" are not discovered in the field investigation, it is possible to rapidly incorporate increasingly complex information into the model. The problem is that as the model becomes more complex or new data require a major model restructuring, the time required to recalibrate the model and become satisfied that the model is reasonable may not fit the field work schedule. It appears that it is best to schedule field work in stages. There should be sufficient time between stages to adequately analyze the data in hand and plan additional data acquisition. Such an approach makes the best use of a model's analytical power and would help plan the most effective use of field resources.

Model Application

The case studies demonstrated the usefulness of groundwater models. At Comstock the model was coordinated with field work, used for hypotheses testing and aided in understanding the aquifer behavior. At Southwest Ottawa County Landfill and Production Plated Plastics (PPP) the models combined likely boundary conditions with known complexities in the aquifer systems. The models included all the known data and provided realistic simulations that would not otherwise be possible. The effect of the complex lens system on the flow field was simulated at Southwest Ottawa. And at PPP the complex aquifer geometry, inhomogeneities and artificial recharge and withdrawals were all incorporated in the model. The calibrated models are powerful analytical tools, and are ready for use in designing purge well systems, or evaluating other management alternatives. Both steady state and unsteady analyses are possible.

Once a model is calibrated, additional applications are relatively easy. It is possible to quickly simulate the effects of a proposed purge well system. The model also provides a basis for evaluating pump tests and new field data. At PPP the model helped direct placement of additional monitoring wells.

The investigation of various management options and assistance as a design tool are where the benefits of modeling are likely to be greatest. Much more information is required at Comstock before the aquifer is sufficiently understood to begin evaluating management options. At Production Plated Plastics different purge well schemes have been simulated and preliminary design of a purge well system is proceeding with the assistance of the model. Southwest Ottawa County Landfill is ready to start investigating management options and proceed to preliminary design. Some management options were tentatively investigated, but DNR and the County have yet to agree on future action at the site. So there is no guidance on the types of management options that should be seriously investigated. The model is ready for evaluating preliminary designs for remedial action. Final design at each site will require an iterative process between modeling, data collection and field testing.

Parameters for Mass Transport Models

Parameter estimation is a difficult task in mass transport modeling. There are few published estimates of dispersion coefficients or other parameters, no well developed field estimation techniques, and even continuing disagreement on the nature of some of the parameters. A lot of information about the source strength and duration, and plume propagation is ideally needed, but rarely available. The usual procedure in groundwater investigations is to establish that there is a contamination problem and define its limits. Little effort is made to monitor the system over time, thereby missing valuable data for analysis. Periodic sampling of monitoring wells provides a valuable time history of the contamination. This was done at PPP. It provided the information necessary to estimate dispersion coefficients and indicated groundwater velocities. Several other sites were evaluated and techniques developed to estimate dispersion coefficients. These estimates provide a basis for estimating dispersion coefficients at other Michigan sites where inadequate site data are available. The estimates tend to be low when compared with other published values, but are not inconsistent. This work should be valuable for future mass transport modeling.

AQUIFEM

AQUIFEM proved to be a good general flow model. It is flexible and easy to use, with excellent documentation. The solution is stable and accurate. It can be sensitive to specified aquifer bottom elevations; if they are too high dry nodes appear which cause numerical problems. It is a 2-D analysis, so 3-D results cannot be expected; but for most situations this should be sufficient.

Analytical Mass Transport Models

Analytical models are quick and easy to use and very inexpensive to run. They are developed for uniform flow in a homogeneous, infinitely extensive aquifer. As a result, any analysis with them is very simplified, but for most situations they may be appropriate, especially for a first analysis. At Comstock an analytical model was used to test whether a suspected source that was not directly upstream of the known contamination could be responsible for the contamination. A conservative average seepage velocity from the flow model was used, and a range of dispersion coefficients were tried. This type of analysis works well, it is easy to apply, the results are field verifiable, and it greatly aids in evaluating the potential impacts of dispersion.

Analytical models were also used at Production Plated Plastics. An average seepage velocity along a streamline was used along with a range of estimated dispersion coefficients. An outline of the plume could be generated at any point. It is an effective analysis.

GEOFLOW

The primary constraint which will face a user of a fixed grid finite element mass transport model, such as GEOFLOW, will be the necessity to employ a sufficiently large number of elements to minimize the numerical oscillation and dispersion. Realistically, it is not always possible to maintain the numerical Peclet number (Pe) in the desired range, and as a result, some numerical errors will be present. This will be particularly significant for mass transport which is convection dominated (as is the situation for the PPP site study).

Additional problems encountered in the present study were related to the shape of the finite element. The GEOFLOW mass transport model employs linear quadilateral isoparametric elements which consist of four nodes connected by straight lines. Undesirable elements are those which do not conform closely to a rectangular shape. If an element can maintain a nearly rectangular outline, then a solute will migrate through without having a residual concentration buildup. Likewise, rectangular shaped elements will prevent large accumulations at edge nodes.

There was no difficulty in maintaining an appropriate numerical Courant number in the regional analysis. According to that criterion, the time step could have been increased approximately five times without affecting the modeled convection. The effect of increased time step upon the dispersion is not clear.

GEOFLOW has no numerical accounting of solute mass conservation. Such a check should be made at selected times to insure the accuracy of the predictions. This is especially true of GEOFLOW inasmuch as predicted concentrations which drop below a selected arbitrary baseline value are equated to that value at the end of each time increment. As a result, it is possible that mass conservation errors may be accumulative, especially when Peclet numbers are high and significant numerical oscillation is present.

The use of GEOFLOW for the regional aquifer problem has demonstrated that convection-dominated flows on a regional scale may be difficult to model accurately with a fixed grid finite element model. It is important to keep the numerical Peclet number sufficiently low such that numerical oscillations do not obscure the movement of predicted fronts; D'Appolonia personnel have suggested that a practical upper limit to Pe is about five. An appropriate Pe can be maintained by employing smaller elements or by increasing the dispersivities. With the former one may be restricted by computer size, but that could be partially overcome by modeling a more localized region rather than an entire aquifer. With the latter, greater dispersion will be predicted, and will not be representative of the physical system. Whether this is tolerable must be assessed for each individual situation. It is useful to keep in mind the significant uncertainties associated with dispersivity estimates and allow a reasonable variation in the model.

It should be apparent that in contrast to the difficulties surrounding fixed-grid finite element modeling of mass transport, the hydrodynamic solution does not have similar problems. The GEOFLOW model provides an accurate and versatile flow solution, one representative of many available finite element models, including AQUIFEM. There is no difference in the accuracy between GEOFLOW's flow model and AQUIFEM. But AQUIFEM is easier to use and better documented.

At Production Plated Plastics it may be appropriate to take the regional flow predictions and delineate a more localized flow region that would contain the plume movement. Such a procedure would place a more refined grid in the region of interest, and reduce Pe. It would be necessary to accurately match the regional flow and ensure that the plume movement is not affected by the artificial boundaries. Detailed sensitivity analyses would be required. While this is a reasonable approach, there is no guarantee that it would entirely overcome the problems encountered in the regional application of GEOFLOW. Additional investigation would be required.

Alternate flow and mass transport models are available which utilize characteristic methods or combine characteristic and random walk concepts. These may be more desirable than fixed-grid finite element formulations when the mass transport is convection dominated.

USGS Mass Transport Model

Values for the Peclet Number significantly greater than one imply convection dominated problems which cause numerical dispersion problems in finite element models. These conditions must always occur for the regional type of aquifer problems with grid sizes of several thousand feet and dispersivities of at most tens of feet. The USGS Method of Characteristics Model was found to be fairly accurate for the problems that were investigated in this study. Very little numerical dispersion was apparent in the computed results, which is the primary advantage of this particular model.

Problems were noted in the various solutions where the ratio of longitudinal to lateral dispersivity was 10 or more. Under these circumstances, negative concentrations began to appear at the edges of the computed plumes. These are not suppressed in the computations. The magnitude of the negative values was always much less than the magnitudes of the maximum concentrations, but it is not clear that this problem would not become worse under certain circumstances.

There were many practical problems with the implementation of the numerical code. One problem was with the explicit nature of the code and the fact that the computational time step is set internally within the program. In the vicinity of pumping wells, the flow velocities can be very high and the computational time step correspondingly small, requiring an excessive number of calculations to cover a given simulation period. This situation is problem specific, but [illegible] considered in the problem formulation to avoid excessive costs [illegible] with a particular simulation. Another problem that is not specific to a particular numerical code is the lack of computational resolution for small travel distances. This was especially true for the PPP simulation and necessitated using a smaller grid. This problem will arise in any numerical code that requires a constant grid size. At least the small size of the slug in a large grid does not create serious computational inaccuracies with the USGS model. Finally, problems arose in specific applications with the model. The model is not set up to compute an initial steady state, so any transient calculation first requires a separate simulation to get a reasonable initial condition. The code will allow steady state flow solutions, but simply doesn't allow starting a transient calculation from a computed steady state. This would represent a significant improvement in the model. Other than that, the code is somewhat limited in the number of options that are available, but does have the capabilities necessary to solve most commonly encountered problems. Some of the procedures to be followed are a little obscure and a certain amount of familiarity with the code helps in the setup of problems.

Comparison of Mass Transport Models

All three mass transport modeling methods were applied at Production Plated Plastics. If a cost/benefit analysis was made of the three methods, the analytical models would be found the most effective. The analysis possible with the analytical models was comparable to the other methods at PPP. It was within the uncertainty limits present in the other mass transport models. The costs and effort needed to apply the analytical models were a small fraction of that required in the other methods.

The ease of use makes analytical models the obvious first step in any mass transport modeling (after an adequate flow model has been developed). For many, if not most, situations, it would not be justifiable to use more than an analytical model. Only when the complexities of the situation, and the project goals require more refined analysis, and there is sufficient data should a numerical mass transport model be tried.

Finite element mass transport models are accurate for some conditions, but there are significant problems when applying them to regional simulations. The Peclet number criterion appears to be critical and must be carefully evaluated before using a finite element model. Ideally Pe should be less than one, but it may be acceptable to be an order of magnitude higher. It was a major effort to apply GEOFLOW at Production Plated Plastics and the results were not entirely satisfactory. The lessons learned from this effort will make future applications easier, but it will still be no small task. If numerical dispersion is controlled, the method is capable of incorporating aquifer complexities, recharge and withdrawals and their effects on the flow pattern and velocity variation.

The method of characteristics methodology is numerically more accurate than finite elements in convection dominated problems. The USGS Mass Transport Model is awkward to use and interpret, but with a little effort it is workable. It is also able to incorporate aquifer complexities, recharge and withdrawals.

The models are used to project what the plume size and location might be. This is most valuable when trying to analyze the effects of taking no remedial action. They are also helpful when trying to locate a plume that was known to pass through an area, as happened at PPP. From the study it is not clear whether there would be any significant benefit from using a mass transport model to analyze the effect of a purge well system on a plume. A flow model is certainly needed to ensure that an adequate capture zone is developed by the wells.

CHAPTER 10

SUMMARY AND CONCLUSIONS

This project has developed the State of Michigan's capability to use groundwater modeling. Appropriate computer programs were selected, tested and used at three sites. Application methodologies were developed and evaluated in each case study. The study demonstrated that groundwater models are valuable analytical and management tools.

The study demonstrated a number of the strengths of groundwater modeling. A model can be used to test the reasonableness and consequences of working hypotheses. Modeling can be coordinated with data collection. The model can help direct where new data should be collected, and with new data the model can be improved. Models can be used to simulate conditions under various management alternatives. Results help determine which management plan can best minimize the effects of contamination. And although these case studies have not yet reached final design stage, modeling can be closely coordinated with the final design and implementation of a management plan. Groundwater models greatly extend the range of analysis possible in complex groundwater systems.

Technical literature was reviewed to determine the state-of-the-art in groundwater modeling and what programs were available. Although hundreds of programs have been developed, only a handful are useable. Useable programs are completely documented, are available, and have been applied to at least one field problem. This situation seems to result from restrictions on availability of programs developed by private and semi-public agencies; poor program documentation, particularly those developed at universities; and difficulties in applying existing programs to field problems.

An individual program is not applicable to all situations. Each program has its unique set of assumptions, strengths and weaknesses. Each project must be carefully evaluated, project goals set, and the analytical needs determined. This was done for each case study.

AQUIFEM was selected as a good general flow model. It is appropriate not only for these sites, but for most general flow problems encountered. It is a two-dimensional flow model that can incorporate anisotropy, heterogeneity, transient conditions and a variety of boundary conditions. It is flexible, relatively easy to use, and very well documented.

Mass transport modeling is a much more complex and less well defined process. Three different methods were tried. Analytical models, which are exact mathematical solutions to very idealized situations, were used. They model a uniform flow field in an isotropic, homogeneous, infinitely extensive aquifer with constant dispersion coefficients. They are extremely easy and inexpensive to use. Two different numerical methods were used: a finite element model, GEOFLOW; and a method of characteristics model, the USGS Mass Transport Model. These are able to incorporate irregular boundary conditions, inhomogeneities and velocity variation in the flow field.

All the models were successfully tested against known analytical solutions. Some of the models were also compared with other numerical models. Additional example problems were run to gain familiarity with the models and observe their behavior under controlled test conditions. As would be expected, boundary conditions greatly influence the final solution. Boundary conditions must be carefully considered in any analysis.

The first case study was Southwest Ottawa County Landfill. Leachate contaminated the aquifer which supplies water to many area homes. The site hydrogeology and contamination plume outline were determined by installing monitoring wells and conducting a resistivity survey. The resistivity analysis was very helpful, yielding detailed information on geometry and depths of low permeability lenses that were affecting the flow field and contaminant movement. The problem was studied hydraulically with AQUIFEM and the data adapted to fit the two-dimensional formulation. Obvious natural boundary conditions were used in a regional model, which was used to determine appropriate boundaries for the more detailed local model. The model developed in a straightforward manner. Calibration involved iterating between the regional and local models until the model reproduced known aquifer behavior. The calibrated model incorporated all the known aquifer complexities. The model is now ready to evaluate management options and begin preliminary design of a remedial purge well system. There is no way, short of this type of modeling, that all the known complexities of this aquifer system could be incorporated into the analysis of management and design plans.

The second case study involved contamination from an unknown source found at Comstock. Groundwater modeling was incorporated into the investigation to determine the source. A very simple flow model (using AQUIFEM) was made using the almost negligible initial data. Field data were incorporated into the model as the field work progressed. The model was not definitive; a model can never be better than its data base. It was used to aid in understanding what might be happening in the aquifer system. The model can demonstrate the interrelationships between known data. It can test the reasonableness and consequences of hypotheses developed to explain aquifer behavior, and can help set criteria to be field checked.

Production Plated Plastics, the last case study, was the focal point of the study. Several domestic wells near the plant were contaminated with chromium. A flow model was developed using AQUIFEM. The flow model provided input to the mass transport models. All three methodologies were applied.

Analytical mass transport models are simple but effective. They should be applied first in any situation where mass transport modeling is required. Only if site complexity, project demands and sufficient data are available should numerical mass transport modeling be attempted. Under these circumstances the USGS Mass Transport Model is useable, since it provides a numerically stable solution. There are problems in applying a finite element model like GEOFLOW to regional mass transport situations. For an effective simulation the Peclet number must be kept low. Therefore, GEOFLOW would be expected to be more effective when applied on a more local scale.

The models were used to project where the plume might be at PPP. Their results were used to help direct field work. Then new field data were incorporated into the model. Projections based on the groundwater modeling analysis were different than those determined by hand calculations. Modifications to the field program based on the modeling results turned out to be correct. The flow model was used to simulate a pump test before it was run, and evaluate the effects of the recharge water on the plume. Several purge well configurations were simulated and the model is being used to help design an effective purge well system.

Groundwater models provide a means of simulating the dynamic response of a complex groundwater system. The impact of proposed activities, such as the location and pumping rates of purge wells, can be estimated before any money is invested in actually initiating the activity. This helps provide effective resource management.

SECTION VI

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